Proposed Technique for Cooperative Spectrum Sensing Optimization through Maximizing the Network Utility and Minimizing the Error Probability

A Thesis submitted in partial fulfillment of the Requirements for the degree of

Master of Technology
In
Electrical Engineering
(Electronic Systems and Communication)

By

BOMMENA PRUTHVIRAJ KUMAR

Roll No: 213EE1287

Department of Electrical Engineering
National Institute of Technology Rourkela
Rourkela, Odisha, 769008, India
May 2015

Proposed Technique for Cooperative Spectrum Sensing Optimization through Maximizing the Network Utility and Minimizing the Error Probability

A Thesis submitted in partial fulfillment of the Requirements for the degree of

Master of Technology
In
Electrical Engineering
(Electronic Systems and Communication)

By

BOMMENA PRUTHVIRAJ KUMAR

Roll No: 213EE1287

Under the Supervision of

Prof. Susmita Das

Department of Electrical Engineering
National Institute of Technology Rourkela
Rourkela, Odisha, 769008, India
May 2015

Dedicated to…

My parents, sister and my brother

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ROURKELA – 769008, ODISHA, INDIA

Certificate

This is to certify that the work in the thesis entitled **Proposed technique for Cooperative Spectrum Sensing Optimization through Maximizing the Network Utility and Minimizing the Error Probability** by **Bommena Pruthviraj Kumar** is a record of an original research work carried out by his during 2014 - 2015 under my supervision and guidance in partial fulfilment of the requirements for the award of the degree of Master of Technology in Electrical Engineering (Electronic Systems and Communication), National Institute of Technology, Rourkela.

Place: NIT Rourkela
Date: 29th May 2015

Prof. Susmita Das
Associate Professor

DEPARTMENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA
ROURKELA – 769008, ODISHA, INDIA

Declaration

I certify that

a) The work contained in the thesis is has been done by myself under the general supervision of my supervisor.

b) The work has not been submitted to any other Institute for any degree or diploma.

c) I have followed the guidelines provided by the Institute in writing the thesis.

d) Whenever I have used materials (data, theoretical analysis, and text) from other sources, I have given due credit to them by citing them in the text of the thesis and giving their details in the references.

e) Whenever I have quoted written materials from other sources, I have put them under quotation marks and given due credit to the sources by citing them and giving required details in the references.

Bommena Pruthviraj Kumar

29th may 2015

ACKNOWLEDGEMENT

It is my immense pleasure to avail this opportunity to express my gratitude, regards and heartfelt respect to Prof. Susmita Das, Department of Electrical Engineering, NIT Rourkela for her endless and valuable guidance prior to, during and beyond the tenure of the project work. Her priceless advice has always lighted up my path whenever I have struck a dead end in my work. It has been a rewarding experience working under her supervision as she has always delivered the correct proportion of appreciation and criticism to help me excel in my field of research.

I would like to express my gratitude and respect to Prof. K. Ratna Subhashini, Prof. Deepti Patra, Prof. Prasanna Kumar Sahoo and Prof. Supratim Gupta for their support, feedback and guidance throughout my M. Tech course duration. I would also like to thank all the faculty and staff of EE department, NITR for their support and help during the two years of my student life.

I would like to make a special mention of the selfless support and guidance I received from my seniors Deepa Das, Kiran Kumar Gurrala and Deepak Kumar Rout during my project work. Also I would like to thank Satish, Manoj, Abhilash, Pavan and Sudeeptha for making my hours of work in the laboratory enjoyable with their endless companionship and help as well and I would like to thank Rati, Divya, and Bishnu for their support in project.

Last but not the least; I would like to express my love, respect and gratitude to my parents, who have always supported me in every decision I have made, believed in me and my potential and without whom I would have never been able to achieve whatsoever I could have till date.

Above all, I thank Almighty, who bestowed his blessings upon us.

BOMMENA PRUTHVIRAJ KUMAR
pruthvirajkumar100@gmail.com

ABSTRACT

Spectrum Sensing is an emerging technology in the field of wireless communication. It is an essential functionality of Cognitive Radio (CR) where it is used to detect whether there are primary users currently using the spectrum. Selection of suitable spectrum sensing technique is an important task, and it depends on accuracy and speed of estimation. Energy Detection technique is the most commonly used method for spectrum sensing. Non-cooperative spectrum sensing i.e. signal detection by single user suffers from several drawbacks. These drawbacks include shadowing/fading and noise uncertainty of wireless channels. Hence, to overcome these disadvantages, a new methodology called Cooperative Spectrum Sensing (CSS) has been suggested in the literature.

This thesis deals with the comparison of conventional spectrum sensing techniques and based on the computational complexity, accuracy and speed of the estimation, suitable sensing method i.e. energy detection technique will be selected. Here, we consider the optimization of conventional energy detection based CSS. In CSS, several CR's cooperatively detect the unused frequency slots called spectrum holes/white spaces. Generally, in CSS at the fusion centre, two data combining techniques are used which are soft combining and hard combining. Hard combining technique has gained importance due to its simplicity and it deals with three decision rules which are 'AND rule', 'OR rule' and 'MAJORITY rule'. In hard combining only hypothesis output will be sent to the fusion centre, which decides about the presence of the primary user.

For optimization, we have considered the network utility function and error probability. The aim of the thesis is to maximize the network utility and minimize the error probability. In order to achieve the goal we have proposed that the optimum voting rule is half voting rule also known as majority rule in 'n out of K' rules and obtained optimal number of cognitive radios by applying the hard decision rules. A method of obtaining the optimal detection threshold, numerically, has been presented. The optimal conditions have been verified through simulation results over an AWGN channel and it is concluded that, in proposed optimization scheme 'MAJORITY rule (half voting rule)' outperformes the 'AND rule' and 'OR rule'. It has been found that the suitable selection of CR can achieve better utility function with minimum error probability for any wireless environment.

CONTENTS

NOMENCLATURE

$x(n)$	: Received signal by the cognitive user in Discrete Domain
$s(n)$	: Transmitted signal from the primary user in Discrete Domain
$s(t)$	: Transmitted signal from the primary user in Continuous Domain
$u(t)$	: Received signal by the cognitive user in Continuous Domain
h	: Channel gain
N	: Number of samples during detection period and Network size
K	: Number of cognitive radios in cooperation
H_0	: Hypothesis 0 (Primary User is absent)
H_1	: Hypothesis 1 (Primary User is present)
P_d	: Probability of detection
P_m	: Probability of miss detection
P_f	: Probability of false alarm
T	: Test statistic
P	: Average signal power primary user
σ_n^2	: Noise Variance
λ	: Threshold value
E	: Energy of received signal
$Q(.)$	: Complementary cumulative distribution of standard Gaussian function
Exp	: Exponential function
SNR(γ)	: Signal to Noise Ratio
τ	: Sensing time

f_s	: Sampling frequency
$Q_f(K)$	: Average probability of false alarm at fusion centre
$Q_d(K)$	: Average probability of detection at fusion centre
$Q_m(K)$	: Average probability of miss detection at fusion centre

ABBREVATIONS

SPTF	: Spectrum Policy Task Force
FCC	: Federal Communication Commission
CR	: Cognitive Radio
MFD	: Matched Filter Detection
CFD	: Cyclostationary Feature Detection
DAB	: Digital Audio Broadcast
DVB	: Digital Video Broadcast
TRAI	: Telecom Regulation Authority of India
US	: United States
PU	: Primary User
SU	: Secondary User
DSA	: Dynamic Spectrum Access
DSAN	: Dynamic Spectrum Access Network
SDR	: Software Defined Radio
xG	: Next Generation Programme
DAPRA	: Defence Advanced Research Project Agency
PDA	: Personal Digital Assistant
CSI	: Channel State Information
DSM	: Dynamic Spectrum Management
IEEE	: Institute of Electrical and Electronics Engineers

AWGN	: Additive White Gaussian Noise
SNR	: Signal to Noise Ratio
SCF	: Spectral Correlation Function
BPSK	: Binary Phase Shift Keying
CSCG	: Circularly Symmetric Complex Gaussian
ED	: Energy Detector

List of Figures

LIST OF TABLES

1

INTRODUCTION

Now a day's requirement of electromagnetic spectrum is growing with the development of new wireless services and applications. Currently, allotment of frequencies will be done by supplying update service with its secure frequency band. Recent wireless services like Wi-Fi, WiMAX, Digital video broadcast (DVB), Digital audio broadcast (DAB) and the Internet, etc. are unlicensed based. Currently 'Spectrum scarcity' is a major drawback due to increase in No.of frequency users.

The concept of Cognitive Radio (CR) provides the opportunity for the unlicensed users to access the licensed band dynamically. Regulatory bodies are very strict while operating radio spectrum bands to ensure the safety to the licensed users. As there is very less amount of unlicensed spectrum allotted to the new technologies, hence it results in a significant quantity of interference caused between the cognitive/secondary user and the PU. In CR system, which is actually a smart wireless communication system, has the prior knowledge of electromagnetic environment, so it instantaneously changes the radio frequency, and the other parameters like the bandwidth and the overall transmit power immediately.

The task of CR is sensing the spectrum. By adopting and sensing, a CR fills the white spaces and serves the users interfering with the LU (LICENSED USER).

The chief difficulty during spectrum sensing is hidden PU issue. It is occurred by many factors, including multipath fading/shadowing, sensing time constraints and noise uncertainty of wireless channels observed by secondary users (SU) while sensing for PU's transmissions. It is due to this reason; a SU is unable to sense the primary user presence. This leads to a CR accessing the licensed band and causing harmful noise to the PU. This drawback will be handled by CSS (using multiple CR's). It is proved, spectrum detection performance will be maximized with an increase of the NOo.of CR's in cooperation.

The first part of this chapter describes the fixed frequency allocation strategy along with the adverse effect of it on the spectrum utilization. The concept of cognitive radio is discussed in brief. This chapter has been concluded by the objective of the work and thesis layout.

1.1 Motivation

The Radio frequency is restricted, this is controlled by the organizations, TRAI (Telecom Regulatory Authority of India) and FCC (Federal Communication Commission) in the US. Now a days all the services like Wi-Fi, Bluetooth, ZigBee, and Wi-MAX, etc. are working based on wireless technology mainly wireless communication domain. This is the fastest growing area of the communications industry over the past few decades. Recently Spectrum Policy Task Force (SPTF) had released a report which shows that mainly radio spectrum is engaged, but some parts of the spectrum (Frequency range) bands are either heavy used, sparse use or medium use under the particular geographical location [1],[2],[3].

Basically, government telecom organizations assign a fixed frequency to a particular service this process is called 'fixed frequency assignment.' This fixed frequency band cannot be used by the other users called unlicensed users. So to overcome the fixed frequency assignment now a days we are going through the dynamic frequency allocation. When the fixed frequency is not in use, then it's resulting in spectrum hole. Empty frequency will be allocateded to a particular service. When the user uses, the particular service is called primary user (PU) or licensed user. But in a defined geographical area frequency remain unoccupied for a long time, so this empty band should be used by the secondary user (SU) also called unlicensed user hence spectrum sensing comes into the picture.

The spectrum hole concept is illustrated in the following figure :

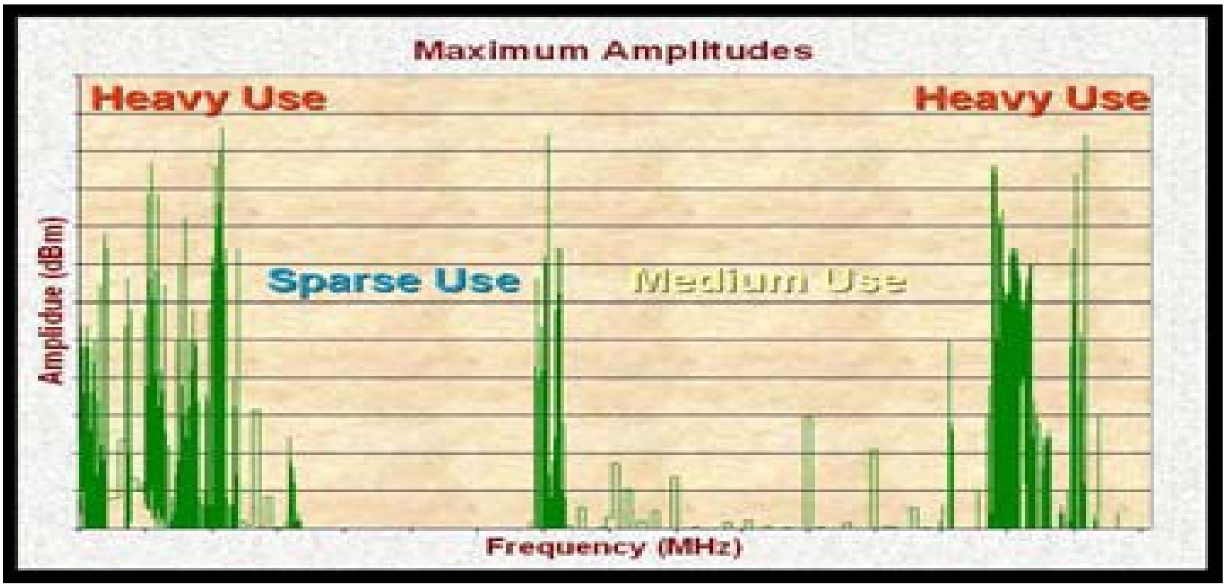
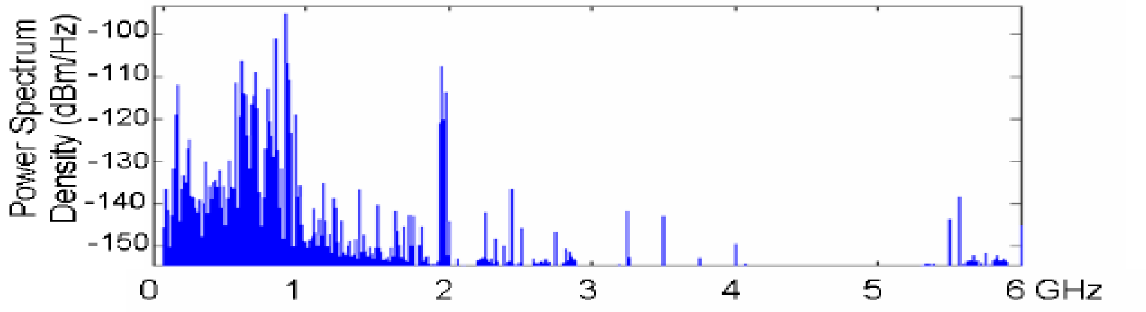


Figure 1-1: Spectrum Utilization

To utilize the licensed spectrum when it's available up to the full extent it is required to give opportunity to the secondary users to borrow unused licensed electromagnetic spectrum frequency band under the condition that it should not affect the PU and doesn't cause interference to the PU. To make this requirement possible an intelligent wireless communication system must require, which must be aware and adapt to its environment and able to select the spectrum band as well as the parameters like carrier frequency, modulation type, bandwidth, etc.

As per the statistics of downtown Berkeley research laboratory on spectrum utilization they have considered the frequency range 0-6 GHz. Frequency ranges from 0-1 GHz has been utilized by only 54.5 percent with the signal strength -100 dBm/Hz. Similarly, other frequency ranges percentages of utilization are gradually decreased with the decrees in the signal strength.



Freq (GHz)	0~1	1~2	2~3	3~4	4~5	5~6
Utilization(%)	54.4	35.1	7.6	0.25	0.128	4.6

Figure 1-2: Measurements of spectrum utilization in downtown Berkeley

Cognitive radio (CR) is an emerging wireless communication technology to deal with underutilization of the electromagnetic spectrum through the process called spectrum sensing, and it allows the SUs to utilize the white spaces, also CR can adapt and aware of its environment due to its ability of parameter (Bandwidth, carrier frequency and transmission power) modification. Spectrum dtection is the key job of the CR system. The process of detecting the absence or presence of PU, CR must check the spectrum continuously, and it is known as Spectrum Sensing. In the spectrum sensing procedure, initially CR will scan the licensed spectrum allotted to the particular service for checking the empty space in spectrum. After the completion of scanning it will give the output, and then CR will choose the appropriate option. If licensed spectrum is free then CR will transmit the data over the unused channel, but at the same time PU uses the licensed spectrum, CR will share the frequency band with the PU by following some limitations like the limit in transmitting power until they find another new white space, and if SU gets the information about another new white space, the CR will jump to the new white space immediately.

1.2 Objective of the Work

The principal aim of this work is to address the optimization of cooperative spectrum sensing. The aim is to maximize the network utility function of a CR system and minimize the error probability at the fusion center. To realize this objective, the following analysis, and investigation are required to be undertaken:

- Study and analyze the conventional spectrum sensing techniques and select the best sensing technique based on speed of the estimation, accuracy and computational complexity. Understand how to optimize the CSS using the best existing spectrum detection.
- Understand the concepts that how to maximize the network utility and how to minimize the error probability to get optimal voting rule, number of CR's and optimum energy threshold value.
- Simulation-based testing through maximizing the network utility and minimizing the error probability to prove its ability to produce a desired or intended result.

1.3 Literature Survey

- A report "The FCC (Federal Communication Commission)" was given by **H. Ronald Coase** in the year 1959. In this report, he had introduced the problem of 'spectrum underutilization' and 'spectrum shortage' [3]. Cognitive Radio (CR) was firstly introduced by **Joe mitola** to overcome the problem electromagnetic spectrum shortage in his Ph.D. essay in the year 2000, [4]. Later on the FCC has given the report on in the year 2005 [1]. The FCC report clearly shows that still there are some parts of licensed spectrum, which remains free/empty for long duration under particular geographical area/location/region.
- Along the same lines, Simon Haykin defines cognitive radio in his paper **"Cognitive radio: brain-empowered wireless communications,"** in the year 2005, [5]. Later on, a new concept has come into the picture that is dynamic spectrum access. It was explained by **Clancy III et.al.** in his Ph.D. essay in the year **2006,** [6]. After that a new word called '**spectrum hole'** came into the picture. This was described by **I. F. Akyildiz et.al.** In his journal, in 2006, [7].
- CR can be aware and adapt to its environment this was explained by **A. Gorcin et.al.** in the year 2007, [8]. Later on Transmitter Detection Techniques came into the picture this was proposed by **P. Karnik et.al** in the year 2004, [9].

- **M. Höyhtyä et.al** explained the spectrum sensing techniques and challenges in his paper techniques and challenges for active spectrum detection**,"** in the year 2007, [10].
- **H. Urkowitz** explained the concept of energy detection in his paper in the year 1967, [11]**.** This concept is older than the idea of cognitive radio. In this paper, it's clearly mentioned that the received signal energy transmitted from the PU is calculated at the CR terminal. This calculation not be needed any before information of primary user signal. Later on comparative study of sensing techniques has been conducted in the paper in the year 2012 by the **Ashish Bagwari et.al**. [12].
- **Tevfik Yucek and Huseyin Arslan** [13] explained challenges, enabling algorithms, standards that employ sensing, approaches, cooperative sensing and multidimensional spectrum sensing in their paper in the year 2009.
- The main idea of 'CSS' has been explained by **G. Ganesan and Y. G. Li**, in their paper in the year 2005.[14].
- CSS in the disturbing environment is explained by **A. Ghasemi and E. S. Sousa,** in their paper in the year 2005. **K. B. Letaief and W. Zhang,** also explained the concept of **Collaboraive communications for CR** in the year 2009.[15].
- CSS optimization is described by **Wei Zhang** and group by considering the error probability for optimization in 2009.[16].
- **Suwen Wu**.group [17] explained how to optimize the number of CR's through maximizing the Network utility function in their paper in the year 2009.
- **Vidyadhar Reddy and G, N.S. Murthy**, explained the CSS optimization by considering both AWGN and Rayleigh fading channel in their paper **"Optimization of CSS under AWGN and Rayleigh channel in CR network"**, in the year 2013.[18].

Previous work [16] showed the optimization of the voting rule and the number of CR's by considering total error rate. In [17], optimization of the number of CR's has been found using network utility function and in [18] CSS optimization has been done for both AWGN and Rayleigh channel, whereas in our work we have optimized the voting rule, number of CR's and energy threshold value by considering both network utility function and the error probability for additive white gaussian noise channel.

In this thesis, we consider CSS optimization using the conventional energy detection method that aims at optimizing hard decision fusion rule, the No.of cognitive radio's and optimal energy detection threshold value. In CSS, we have used conventional energy detection sensing technique to maximize the network utility, minimize the error probability. Distributed CR system is considered in which each CR senses the spectrum individually using conventional energy detection method, then takes local decisions and sends it to fusion center (FC) to make global decisions. For an optimal number of CR's, we have used hard decision rules at the FC to maximize the network utility and to minimize the error probability.

1.4 Thesis Contribution

Optimization of CSS will be done by taking the network utility function and the error probability for the optimal result of the voting rule, the number of cognitive radios and energy threshold. The eventual goal is to maximize the network utility of CR system and minimize the error probability at the fusion center. The contribution of the thesis is given under following points:

- Optimization of cooperative spectrum sensing using conventional energy detection technique has been done to select the best required/suitable optimum voting rule, the optimum number of cognitive radios and optimal energy detection threshold.
- Detail mathematical analysis of the network utility function and the error probability has been carried out to justify the simulation results.

1.5 Thesis Organization

The thesis has been arranged into six chapters. The ongoing section gives the brief introduction to the shortage of spectrum, fixed frequency spectrum allocation strategy, cognitive radio, spectrum sensing, CSS and CSS optimization. The motivation and objective of the thesis have been addressed in the following subsections, although the uttermost subsection explains the entire thesis organization and literature survey.

The thesis has been arranged into six chapters. The ongoing section gives the brief introduction to the shortage of spectrum, fixed frequency spectrum allocation strategy, cognitive radio, spectrum detection, CSS and optimization of CSS. The motivation and objective of the thesis have been addressed in the following subsections, although the uttermost subsection explains the entire thesis organization and literature survey.

Chapter 2: The second chapter discusses the detailed description of cognitive radio, including its history, definitions, need, cognitive tasks and applications. Pros and cons of cognitive radio also discussed in the last subsection.

Chapter 3: This chapter gives the introduction to spectrum sensing technique. It also describes the sensing hypothesis and four basic transmitter detection techniques ED, MFD, CFD and Eigenvalue Based detection. The penultimate subsection presents the validation of the theory with simulation results. Comparison of the three methods has been done on the basis of the simulation.

Chapter 4: This chapter describes the concept of CSS and explains about the different types of cooperative spectrum sensing. Later on this chapter presents various types of hard decision rules and the system model of CR network.

Chapter 5: The fifth chapter describes the optimization of cooperative spectrum sensing. Briefly, it explains the error probability, network utility function, optimization of hard decision combining, number of CR's and optimal energy threshold. The simulation results obtained have been included in order to validate the theory proposed.

Chapter 6: This chapter presents the conclusion to the entire research work carried out and give light to the future work of the research that has been conferred in the thesis.

2

BACKGROUND OF COGNITIVE RADIO

2.1 Introduction

Nowadays, the growth rate of the wireless technology is increasing very fast. The demand of electromagnetic spectrum is expanding just because of the growth of new wireless applications like Cellular networks, Military usage, Emergency systems, and TV white spaces. Similarly, every new wireless technique has its own hardware and operating standards for transmission and reception. Therefore, each and every technique must require its own frequency band. But telecom organizations already have been allotted large part of the spectrum band to the so many services, presently these services became licensed type. Due to this reason lot of competition is there for the unlicensed band to apply it to new technologies.

In most of the country's telecom regulatory bodies are not giving the permission to use the licensed spectrum band. But much time allocated frequency does not used in several geographical locations. Hence, an unlicensed user has a chance to use the spectrum when it is not in use; here by spectrum usage efficiency will be increased. Because of the above reason Dynamic Spectrum Access (DSA) comes into the picture, it's filled up with cognitive radio technology. Further, the chapter describes cognitive radio, it which includes its history, definitions, need, tasks, applications, pros, and cons.

A cognitive radio is also called smart radio. It has the transmitter and receiver parts those are planned in a well manner so that it's automatically choosing the high-quality wireless channel from its neighboring environment. The cognitive radio will provide the reliable communication in a particular band by selecting the parameters to the current wireless scenario. Because of the above reason cognitive radio dynamically managed the spectrum utilization.

2.2 Cognitive Radio: History

The Cognitive radio history is not too old. It is a developing technology. xG communication networks concept widely identified as DSANs. It will provide an opportunity for the secondary mobile users to use the wireless channel by using the methodology of Dynamic Spectrum Acess [7]. Spectrum utilization is the key issue. Spectrum use improvement is going on safely for better operation of a cognitive radio system.

Joseph Mitola III proposed the concept of cognitive radio in the year 1998 at the royal institute of technology [4]. The term cognitive radio came from Software Defined Radio (SDR). Later on the concept of SDR understanding will be often called as cognitive radio it includes with hardware (filter, mixer, detectors, modulators, and demodulators) via software on a computer / embedded system [6].

CR gives a best answer to the drawback of not sufficient frequency utilization, and it is the combination of different technologies. A next generation program (xG) initiated by the Defence Advanced Research Projects Agency (DARPA). This program mainly works on the intelligent radio that is recognized as cognitive radio.

2.3 Cognitive Radio: Definitions

After the definition given by Mitola about CR, there are so many forums, organizations, regulatory bodies and different groups have given the description in several different ways.

According to J Mitola [4], cognitive radio is defined as: The point in which the Personal Digital Assistants (PDAs) are adequately smart in calculation about the radio frequency spectrum and associated peer to peer communication, in order to identify first needs of communication in user context and second to make available the radio spectrum and wireless services to these needs.

- Simon Haykin gives description of CR as follows [5]: CR is an smart and knowledgeable wireless communication system, which is receptive towards its neighbouring and uses understanding by building concept so as to modify its methodology according to the radio frequency stimuli via changing its parameters as modulation type, power to be transmitted, frequency range etc., for the two goals: a) Reliable communication and b) Efficient radio spectrum utilization.

- FCC defines CR as a intelligent radio this can alter the variables according to its operating surrounding [1].
- The definition given by IEEE-USA is as follows [19]: CR system is a radio frequency transmitter which is intelligently devised to identify the empty licensed radio frequency spectrum and make use of it temporarily until the licensed user showed up again, with a condition that it should not cause interference to the licensed user or PU.

Along with these definitions, CR can be defined as: *The radio system that takes input as observation from various actions and adapts itself according to the environment for making intelligent decision in order to reach the user's demands*.

2.4 Need of Cognitive Radio

CR is a very promising technique it uses many technologies simultaneously for solving two major problems [1]:

- Sensing the spectrum, finding the white spaces and utilizing it.
- Operating with different leagues of radio having different parameters.

2.5 Cognitive Tasks: Survey

The CR is reconfiguration in nature. The other processes of cognitive manners are performed by signal processing techniques and intelligent retrieval process. The CR system begins its process with sensing of radio frequency spectrum and concluded with action [5].

The working of conventional CR will be explained with a typical cognitive cycle. The cognitive cycle is the way of communication between CR system and its surrounding [5]. The cognitive cycle can be categorized into three firmly co-dependent online tasks [4], [20]. These three tasks of the cognitive cycle are discussed, and their primary functions are focused under below subsections.

1. Radio-Scene Analysis, which includes the below-mentioned functions:

- Evaluation of temperature interference of the wireless environment.
- Identification of white spaces.

2. Channel finding, which includes the below-mentioned functions:

- Channel State Information (CSI) estimation.
- Channel capacity estimation.

3. Active Management of spectrum and Transmision Power Control.

The task 3 is executed at the transmitter and the rest of two at the receiver. These three cognitive tasks interact with the radio frequency environment forms the cognitive cycle. The transmitter and receiver of the cognitive system must work in synchronization, which necessitate the feedback connection; therefore, the CR is a feedback communication system [5]. The cognitive cycle is illustrated in the following figure 2-1:

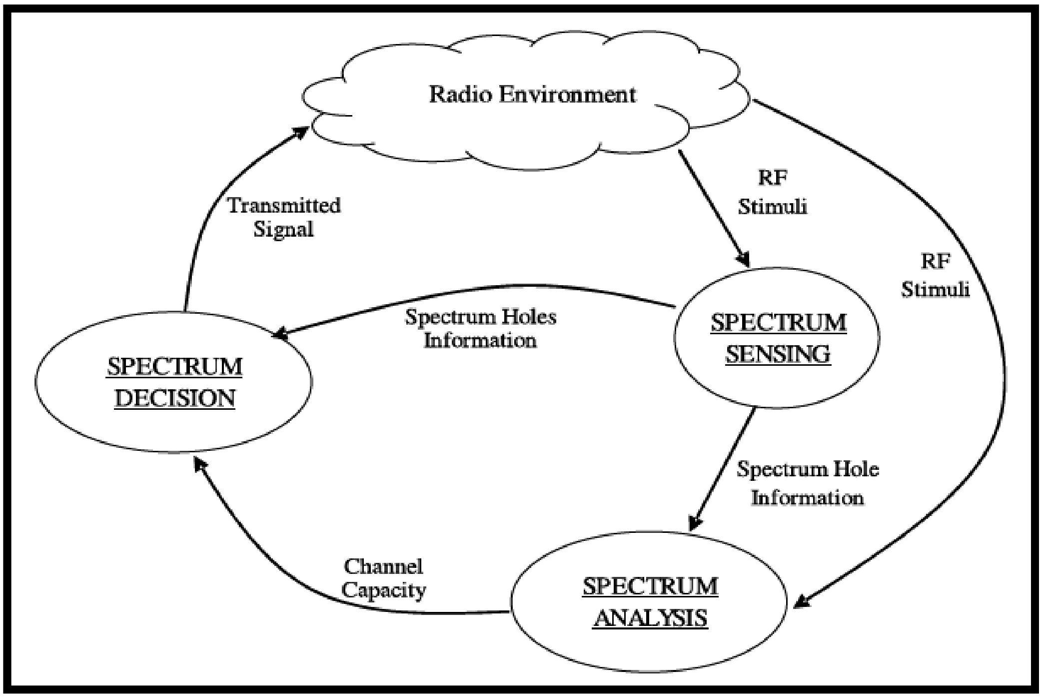


Figure 2-1: Cognitive Cycle

2.5.1 Radio-Scene Analysis

During this part of the cycle, the various radio arrangements are invited to do an appraisal for interference temperature and the spectrum holes. These two terms are calculated at the receiving end and are explained below.

Spectrum Holes:

Spectrum holes are the spaces in the spectrum allocated to a particular user, except in a specific time and geographical region, space is not in use. According to the amount of interference, the spaces or holes are categorized in three parts:

- White spectrum holes, which are free from interference.
- Grey spectrum holes, which are partially occupied.
- Black spectrum holes, which filled the higher interference level.

Spectrum holes and DSA concept are illustrated in figure 2-2. After the spectrum detection operation, the SU’s are permitted to make use of spectrum holes/ white spaces without any restriction, gray spaces with a limitation so they will not cause harmful noise to the PU and finally black areas cannot be used because they are fully occupied and further introduce noise to the PU [5].

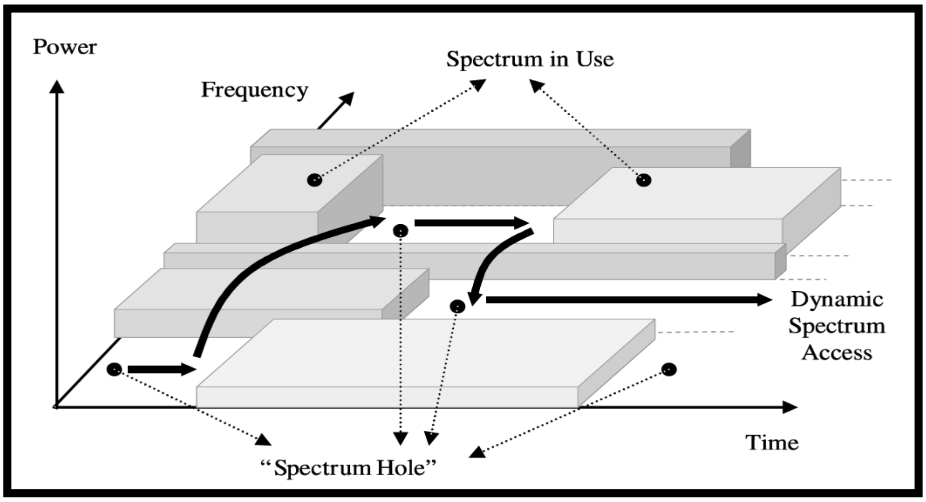


Figure 2-2: DSA and Spectrum Holes

2.5.2 Channel-State Estimation

Channel-State Estimation is also a component of CR [5]. It assesses the channel impulse response and channel's behavior in context with transmitted signal so as the receiver can devise the equalizer and the transmitter can adjust itself and send an appropriate message that can overcome the effects.

2.5.3 Distributed Transmit Power Control

This action is performed in the transmitter as well as receiver parts of the cognitive radio systems in a distributed manner. Each and every user should ensure that the signal that it sends approaches the receiver such that:

- It should be at a higher level than the receiver.
- Below the level at which it causes interference.

2.5.4 Dynamic Spectrum Management

Dynamic Spectrum Management (DSM) works along with the Distributed transmit power control strategy, and both are carried out at the transmitter side. These two functions are correlated to each other; therefore, they are in the same module in the cognitive cycle, as shown in figure 2-1. Dynamic spectrum management algorithm is allotted with the following tasks:

- According to the result of power control transmission and radio scene analysis it picks a modulation strategy that get used to the environmental radio conditions.
- Dependable communication guaranteed throughout the radio channel.

2.6 CR, Applications, Pros and Cons

Cognitive radio has the benefits, pros and cons compared to the conventional one. It has the three qualities observation, adaptability, and intelligence.

Important applications of CR’s:

The evaluation of spectrum sharing and spectrum detection methods makes the use of CR in many geographical areas. Some of them are listed and described below.

- Spectrum utilization improvement
- Economical radio
- Broadband wireless services
- Link reliability enhancement
- Emergency communications

2.6.1 TV white spaces

FCC, the Office of Communication (Ofcom), the ECC of European post and Telecom in Europe all the above mentioned agencies working for the not allocated frequency band use of TV white spaces. After a long time, FCC has released the conditions for using the TV white spaces, so these rules are the final norms of this field. All the other agencies and organizations work still in progress. This progress based on the accessible database in a centralize-fashion of free TV bands, or to sense and obtain spectrum holes in a distributed fashion within TV bands for the use of secondary user's communication.

2.6.2 Cellular networks

In a recent years, the use of cognitive radio in mobile communication playing a major role. Generally in mobile networks, we have a problem of coverage and modify to growth of traffic and the small cell concept (Femto cells) has been presented in 3rd Generation Partnership Project LTE-Advanced and IEEE 802.16m, and in so many companies like PicoChip femtocell (FMC) revolution. In femtocells a femtocell unit plays the role of Base station. By using the cognitive radio, femtocells can detect and evaluate the spectrum availability to continue the coverage and to keep away from the interference to other femtocells and macrocells.

2.6.3 Military usage

Recently, cognitive radio technology is mandatory for the army applications. With cognitive radio, the soldiers will find their enemies plans by communication and protect themselves from harmful tasks. It's compulsory for them to search for transmission opportunities. US government has established next Generation (XG) and SPEAKeasy radio system to utilize the advantages of cognitive radio techniques.

2.6.4 Emergency networks

CR technology is more useful in severe conditions like accidents and natural disasters. The first task is to maintain reliable communication between responders and safety agencies to detect the survivors. The infrastructure of a network is most important thing in a wireless communication system, and it is insufficient to achieve upcoming demands of emergency response. Hence, to overcome this situation an opportunistic radio spectrum usage provided by the cognitive radio would be used to understand effective transmission. By using the cognitive radio technology, we can quickly locate the exact place of survivors in any environment, improve the reliability and communication efficiency. Energy efficiency is a most important factor it depends on the battery life.

Pros of CR:

- Efficient spectrum utilization
- Dependable communication
- Less coordination required than the conventional radio
- Flexible regulation

Cons of CR:

- Security issues
- Maintaining high data rate
- Pricing issues at the end-user
- Regulatory matters
- Loss of control
- Incorrect decisions about spectrum occupancy for hidden primary user and spread spectrum user

2.7 Important Organizations working on CR

- Federal Comm Commission (FCC)
- IEEE - Institute of Electrical and Electronics Engineers
- DARPA - Defence Advanced Research Projects Agency
- SDR Forum - Software Defined Radio Forum
- BWRC - Berkeley wireless research center

3

PERFORMANCE COMPARISON OF CONVENTIONAL SPECTRUM SENSING TECHNIQUES IN CR NETWORKS

Spectrum detection is a important prerequisite job of the xG network [11]. CR is devised to be conscious and receptive towards the variations in the wireless environment. Spectrum detection facilitates the CR to acclimate its surroundings via identifying spectrum holes.

3.1 Introduction

A fundamental demand of CR system is that the unlicensed users should compulsorily catch the existence of the licensed user in the licensed radio spectrum band in prior to make use of the band and jump out of it instantaneously if the associated licensed user comes up for sidestepping the interference to the authorized users [21].

The most competent approach to identifying white spaces is to sense the authorized users in the territory of the cognitive user. Spectrum detection is yet in its evolving phase. It is problematic for the cognitive user to sense the LOS channel b/w the cognitive user and primary user transmitter. Thus, the transmitter detection based spectrum sensing is an important issue to deal with [11].

A fundamental demand of CR system is that the unlicensed users should compulsorily catch the existence of the licensed user in the licensed radio spectrum band in prior to make use of the band and jump out of it instantaneously if the associated licensed user comes up for sidestepping the interference to the authorized users [21].

The most competent approach to identifying white spaces is to detect the authorized users in the territory of the cognitive user. Spectrum detection is yet in its evolving phase. It is problematic for the cognitive user to sense the LOS channel b/w the cognitive user and the primary user transmitter. Thus, the transmitter detection based spectrum sensing is an important issue to deal with [11].

3.2 Spectrum Sensing Hypothesis

The transmitter detection concept is to identify the weak signal transmitted from a PU to the CU. The heart of spectrum detection is the binary detection speculation and can be modeled as follows:

$$x(n) = w(n) \qquad H_0 \qquad n = 1, 2, 3 \ldots\ldots\ldots\ldots\ N \tag{1}$$
$$x(n) = h(n)\, s(n) + w(n) \qquad H_1 \qquad n = 1, 2, 3 \ldots\ldots\ldots\ldots\ N$$

Where $x(n)$ the received signal by cognitive user is, $s(n)$ is transmitted signal from PU, $w(n)$ is Additive White Gaussian Noise (AWGN) and h is the channel gain. The hypothesis H_0 , H_1 are described as:

H_0: Primary user is active

H_1: Primary user is inactive

From this hypothesis the following three essential metrics can be drawn [22]:

- The probability of detection: Channel is vacant and declared as vacant.
- The false alarm probablity: Channel is empty and reported as occupied.
- The probability of miss detection: Channel is occupied and declared as vacant.

In terms of probability these metrics can be defined as:

$$P_d = prb\{{}^{H_1}/_{H_1}\}$$

$$P_f = prb\{{}^{H_1}/_{H_0}\}$$

$$P_m = prb\{{}^{H_0}/_{H_1}\}$$

3.3 Conventional Spectrum sensing techniques

An important task of CR is detecting the spectrum in which, the SU's must be needed to detect the presence of PU's in an allocated radio band. In case of the presence of PU, secondary users are required to leave the frequency band as soon as possible to avoid harmful interference.

The below figure gives the meticulous categorization of spectrum detection methods. They are extensively categorized into two types, one is sensing by transmitter (Signal Processing Techniques) and other is cooperative detection. In transmitter detection methods, the received signal assessment is the key concept, and the transmitter detection techniques are also known as non-cooperative detection techniques.

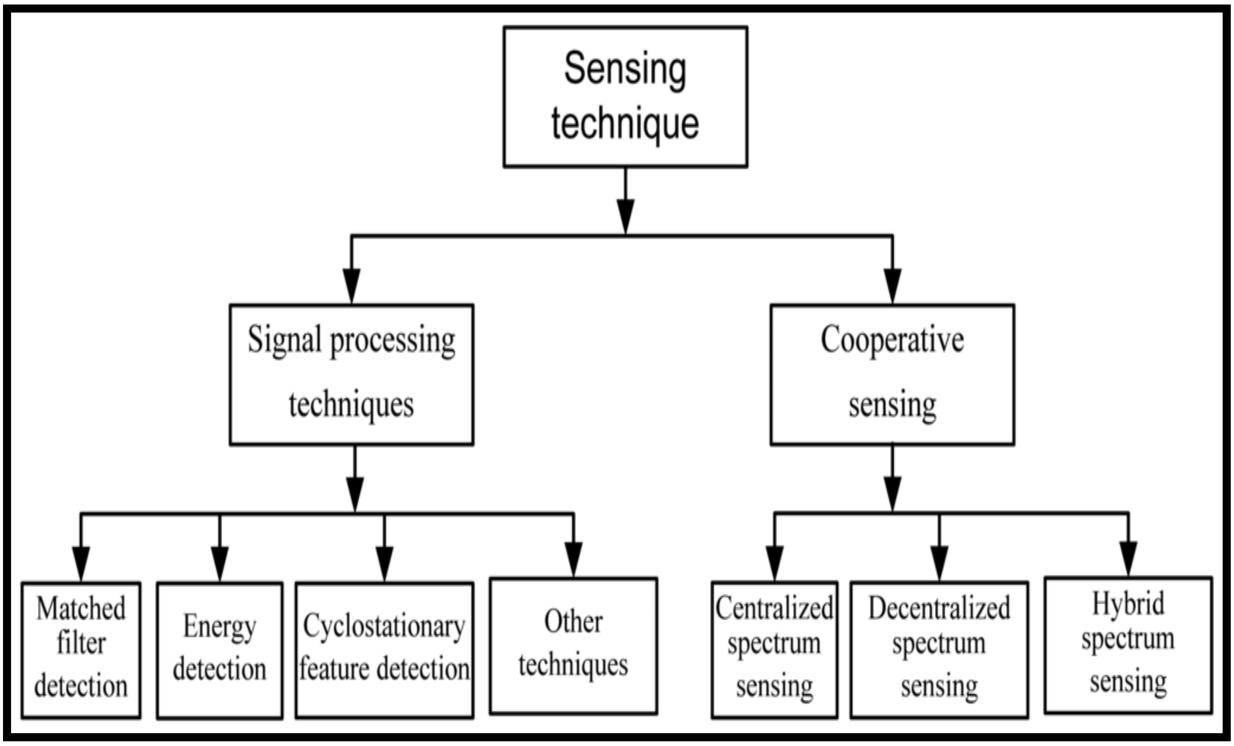


Figure 3-1: Classification of Spectrum Sensing Techniques

The transmitter detection technique is again categorized into Matched Filter Detection (MFD) Energy Detection (ED), Cyclostationary Feature Detection (CFD) Techniques and other techniques include Eigenvalue Based Detection also called blind spectrum sensing. Following subsections gives the detailed explanation about these four techniques.

3.3.1 Energy Detection

When the primary user signal is unknown, then the mostly used spectrum detection technique is ED. The underlying concept at the bottom of Energy Detection is a calculation of the power or energy the PU signal received at the cognitive user terminal. The basic diagram of ED is presented below.

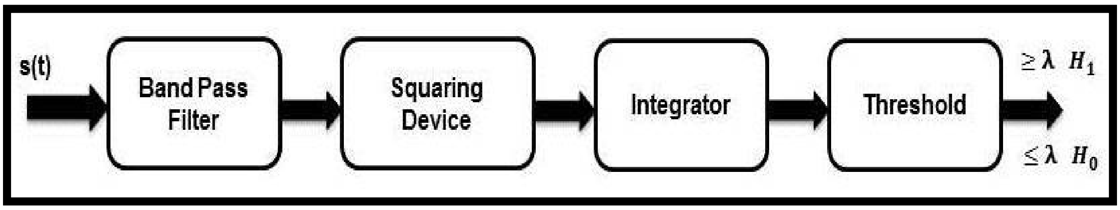


Figure 3-2: Block Diagram of Energy Detection Technique

To find the energy of PU signal the filtered signal from the BPF is squared and integrated so as to calculate energy and then the final output is compared with a pre-set threshold value for spectrum occupancy details [23].

The technique is most commonly used because of low computational complexities. ED method is also known as Blind Detector as it only estimates energy is disregarding the type and properties of the signal. Rather than this fact, the ED also suffers from some drawbacks:

- For a given probability sensing time will be more
- Sensing Performance also depends upon the noise power
- It is very difficult to discriminate between the PU signal and the cognitive user signal
- This technique is not suitable to detect spread spectrum signals.

The calculation of energy can be done by following equation:

$$T(y) = \frac{1}{N} \sum_{n=1}^{N} |y(n)|^2 \quad (2)$$

Where, $T(y)$ is the test statistic, N ($N = \tau f_s$) is the No. of samples under the observation. For a single value of λ, occurance of licensed user can be declared.

$T(y) > \lambda$ H_1 = Primary user is active

$T(y) < \lambda$ H_0 = Primary user is idle

Where, we considered the complex-valued PSK signal and CSCG noise case. According to PDF of test statistic, the detection probability, the false alarm probability and the probability of miss detection can be written as:

$$P_d(\lambda, \tau) = Q(\left(\frac{\lambda}{\sigma_u^2} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{2\gamma+1}}) \quad (3)$$

$$P_f(\lambda, \tau) = Q\left(\frac{\lambda}{\sigma_u^2} - 1\right)\sqrt{\tau f_s}) \quad (4)$$

$$P_m(\lambda, \tau) = 1 - P_d(\lambda, \tau) \quad (5)$$

Where $Q(.)$ function represents the complementary cumulative distribution of standard Gaussian function and λ represents the pre-set threshold value.

3.3.2 Matched Filter Detection

A linear matched filter is designed to improvise the SNR for a given i/p signal in the digital signal processing to remove additive stochastic noise. In this method correlation of two signals will be done. One signal is transmitted signal and another signal is time shifted version of i/p signal and finally compares the output with the predefined threshold.

In the diagram shown below, the PU signal $x(t)$ convolved with the time shifted version of prior signal$s(t)$. Finally the output is compared with the predefined threshold value [24].

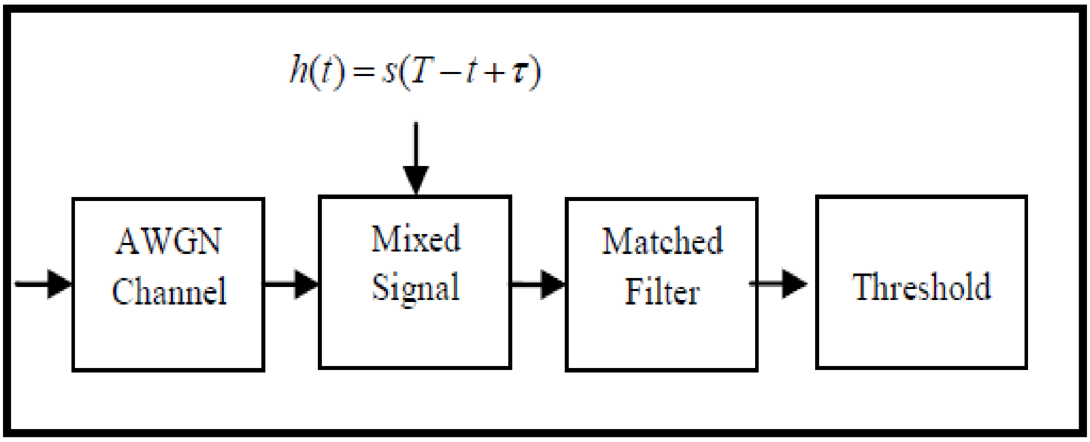


Figure 3-3: Block Diagram of Matched filter detection

The matched filter detection algorithm is developed based on the schematic below

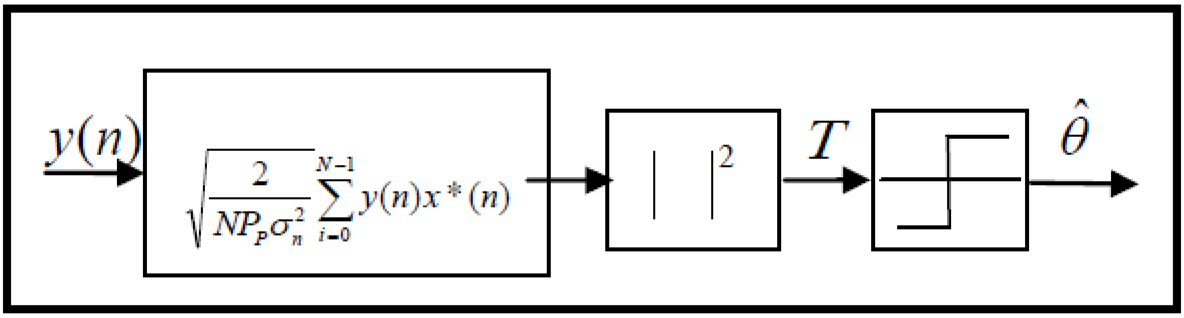


Figure 3-4: Schematic representation of Matched filter detection

The decision statistic of matched filter is given by:

$$T = \sum_N y(n)\, x(n)^* \tag{6}$$

$$v = \sum_{i=0}^{N-1} y(n)\, x(n)^* \tag{7}$$

$$T = \left| \sqrt{\frac{2}{N\, P_p \sigma_n^2}}\, v \right|^2 \tag{8}$$

Where x(n) is the modulated GMSK signal, N is the number of channels, σ denotes the noise power. The decision to detect the signal is given by the hypotheses below:

$$T > \lambda \qquad H_1 \tag{9}$$

$$T < \lambda \qquad H_0$$

γ is the threshold of the matched filter detection. H0 and H1 denote the hypotheses corresponding to the absence and presence of PU respectively. Threshold value is given by:

$$\gamma = \frac{P_p}{\sigma^2} \tag{10}$$

Where P_p is the average power.

3.3.3 Cyclostationary Feature Detection

If we consider the noise uncertainty, cyclostationary detection is preferable than the energy detection technique. This technique mostly depends on cyclo stationary attributes like mean and autocorrelation. This method outperforms the energy detection method, particularly for low SNR values. Suppose if any signal is showing the periodicity property then those signals is called Cyclostationary signals. Noise is the wide sense stationary process it doesn't exhibits the properties stated above. Hence, extraction of the noise signal from the received signal is feasible using any spectral correlation function. A cyclostationary feature is purposely encapsulated along with the physical property of the signals; this feature can be efficiently generated and identified with the use of moderate intricacy receiver and transmitter.

The block diagram of cyclostaionary feature detection is described in below figure.

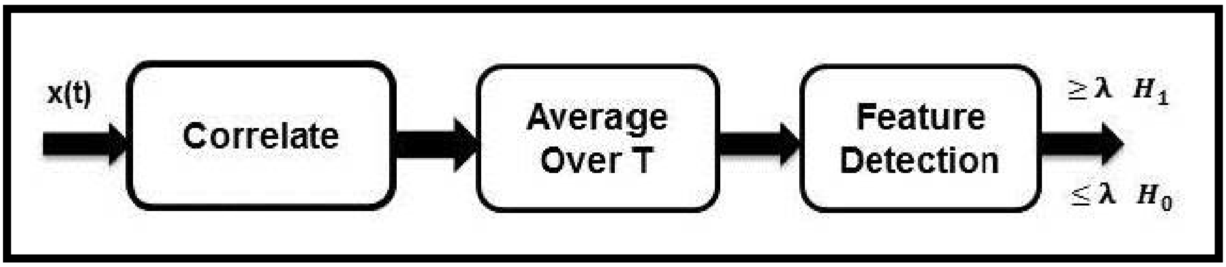


Figure 3-5: Block diagram of cyclostaionary feature detection technique

Cognitive user recognizes the arbitrary signal with a distinct modulation type, even though if it exists with a hypothetical noise by employing periodic information like autocorrelation and mean of the PU signal, and the autocorrelation and mean can be evaluated via Spectral Correlation Function (SCFs).

The CFD technique has the intelligence to distinguish the primary user’s signal and noise; therefore, it outperforms the Energy Detection and Matched Filter Detection methods discussed above. But larger observation time and more computational complexity are the two drawbacks.

For a particular threshold value λ the probability equations can be given as follows [25]

$$P_d = prob(T > \lambda|H_1) = Q(\sqrt{\frac{2*SNR}{\sigma_n^2}}\frac{\lambda}{\sigma_a}) \quad (11)$$

$$P_f = prob(T > \lambda|H_0) = \exp(\frac{-\lambda^2}{2*\sigma_a^2}) \quad (12)$$

$$P_m = 1 - P_d \quad (13)$$

Where

$$\sigma_a^2 = \frac{\sigma_n^2}{2N+1} \quad (14)$$

3.3.4 Eigenvalue Based Detection

Eigenvalue Based detection is also called blind spectrum sensing technique. This method mostly used at low SNR values. Eigenvalue based detection mainly according to the Eigenvalues of the received signal covariance matrix at the SU's. In EVBD the detection threshold value can be calculated on the basis of the random matrix theory. By using this method we can achieve a detection probability high and false alarm probability small without knowing the data of PU signal, noise power and channel information. Hence noise uncertainity drawback can be overcome by this method unlike ED [26]. EVBD doesn't depends on the synchronization unlike MFD.

In MFD method, statistical co-variance matrix includes the signal sample correlations. In the presence of orrelated signals EVBD performs well than the ED. EVBD has more computational complexity than the Energy Detector. There are three primary EVBD techniques, those are divided as per the test results used to detect the signal. In every technique, the test statistic always compares with a predefined threshold value.

The three methods are

- Minimum, maximum Eigenvalue (MME)
- Energy with maximum Eigenvalue (EME)
- Minimum Eigenvalue Detection (MED).

MME: The proportion of the Eigenvalues (maximum to minimum) of the sample COV-matrix used as the test data points. **EME**: The propotion of the average received signal power to least Eigenvalue. **MED**: The highest Eigenvalue is taken as the test data point to get the comparision with a predefined threshold value. The system model used is same as that of the energy detection system design. The system model used is same as that of the energy detection system design.

Statistical covariance matrices for maximum and minimum eigenvalue detection are

$$R_Y(N) = \frac{1}{N}\, YY^T \tag{15}$$

$$R_{HX}(N) = \frac{1}{N}\, H_X {H_X}^T \tag{16}$$

$$R_\eta = \frac{1}{N}\, \eta\eta^T \tag{17}$$

The combination of maximum and minimum eigenvalue of the sample covariance matrix is used as the test data point to sense the primary signal. λ_{max} and λ_{min}be the maximum and minimum eigenvalue of the covariance matrix. The first threshold value is given by

$$\gamma_1 = \frac{(\sqrt{N}+\sqrt{K})^2}{(\sqrt{N}-\sqrt{K})^2}\,(1 + \frac{(\sqrt{N}+\sqrt{K})^{\frac{-2}{3}}}{(\sqrt{N}-\sqrt{K})^{\frac{1}{6}}}\; F_1^{-1}(1 - P_{fa}) \tag{18}$$

Where,

K = No. of Cognitive Radios

$F_1^{-1}(\,)$ = Is the Tracy Widom distribution function

The second threshold value is given by:

$$\gamma_2 = \frac{\gamma_1 + 1}{\gamma_1} \tag{19}$$

Then decision can be done

$$T = \frac{\lambda_{max}}{\lambda_{max} - \lambda_{min}} \tag{20}$$

$$\begin{array}{ll} T > \gamma_1 or\, \gamma_2 & \qquad H_1 \\ T < \gamma_1 or\, \gamma_2 & \qquad H_0 \end{array} \tag{21}$$

3.4 Simulation Study

With a view to verifying the hypothesis of detection, the simulations were made for ED, MFD, CFD and Eigenvalue based detection in MATLAB. The transmitter signal or the PU signal is a random bit stream multiplied with a sinusoidal carrier signal to generate BPSK modulated wave. This signal is transmitted in AWGN channel. The detection performance has been analyzed on the basis of following cases:

3.4.1 Simulation Results and Performance Analysis

In case of Energy detection technique, the plot has been drawn by considering the parameters false alarm probability, detection probability and SNR.

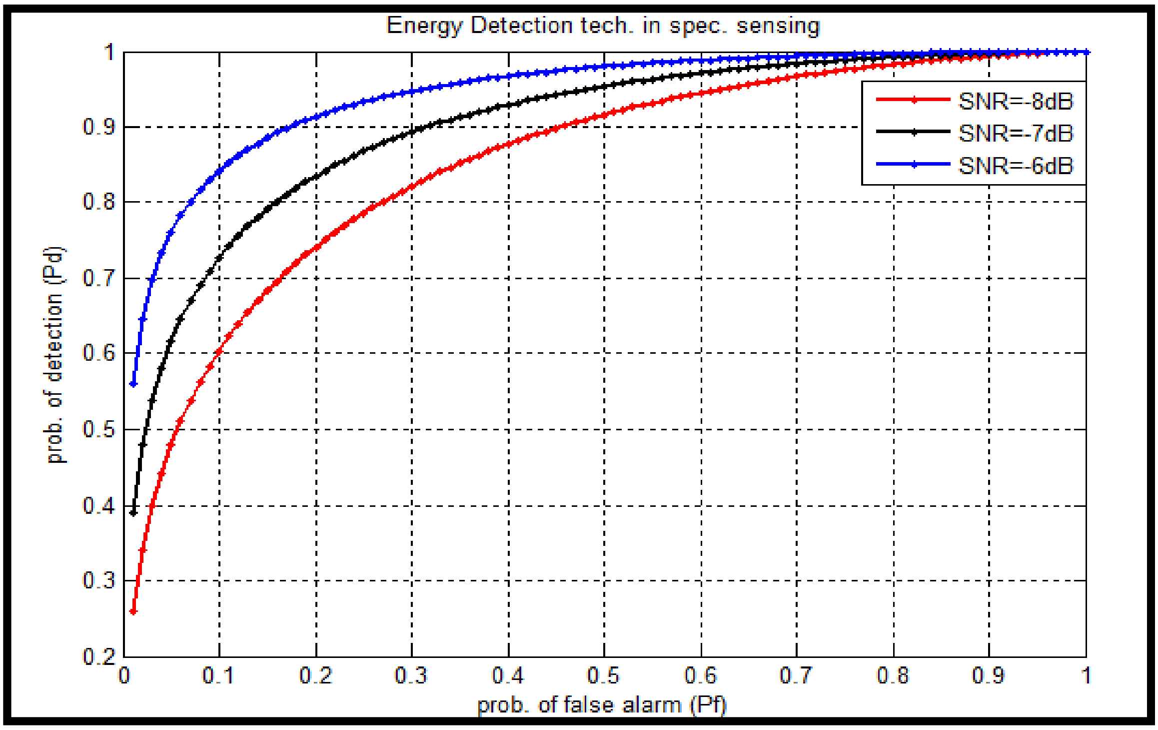


Figure 3-6: Receiver Operating Characteristics for Energy Detection Technique Pf vs. Pd

SNR / P_f	-8 dB	-7 dB	-6 dB
0.1	0.60	0.72	0.85
0.4	0.88	0.93	0.97
0.8	0.98	0.99	1

P_d

Table 3-1: Receiver Operating Characteristics for Energy Detection Technique Pf vs. Pd

In the above figure we have varied the signal to noise ration values from -8 dB to -6 dB. When the SNR is -8 dB and Pf is 0.1 then the probability of detection is 0.6. When the SNR is -7 dB and Pf is 0.1 then the probability of detection is 0.73. When the SNR is -8 dB and Pf is 0.1 then the probability of detection is 0.85. Finally from the above graph we conclude that when the SNR is increased from low to high at a particular value of Pf probability of detection is increasing.

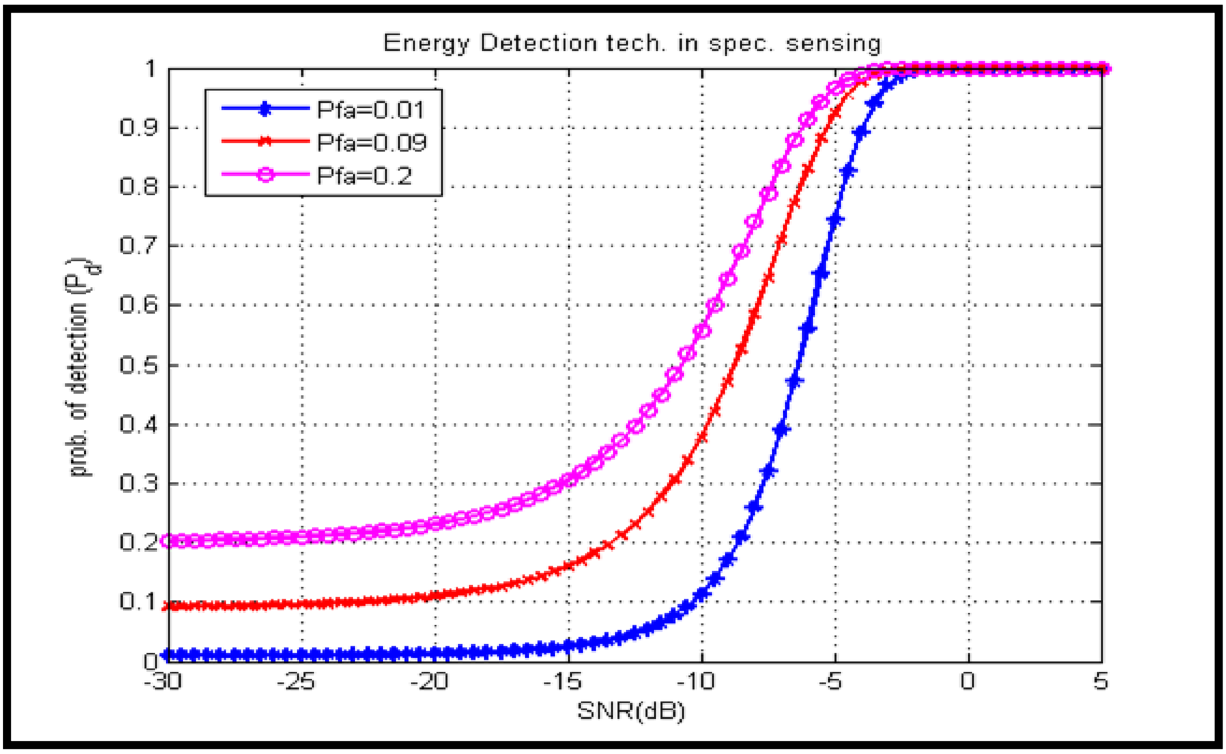


Figure 3-7: Receiver Operating Characteristics for Energy Detection Technique SNR vs. Pd

P_f / SNR	0.01	0.09	0.2
-25 dB	0.01	0.1	0.21
-10 dB	0.1	0.39	0.56
-5 dB	0.75	0.92	0.98

P_d

Table 3-2: Receiver Operating Characteristics for Energy Detection Technique SNR vs. Pd

In the above figure we have a varied false alarm probability values from 0.01 to 0.2. When the Pf is 0.01 and SNR is -10 dB then the detection probability is 0.1. When the Pf is 0.09 and SNR is -10 dB then the detection probability is 0.4. When the Pf is 0.2 and SNR is -10 dB then the detection probability is 0.55. Finally from the above graph we conclude that when the Pf is increased from low to high at a particular value of SNR detection probability is increasing.

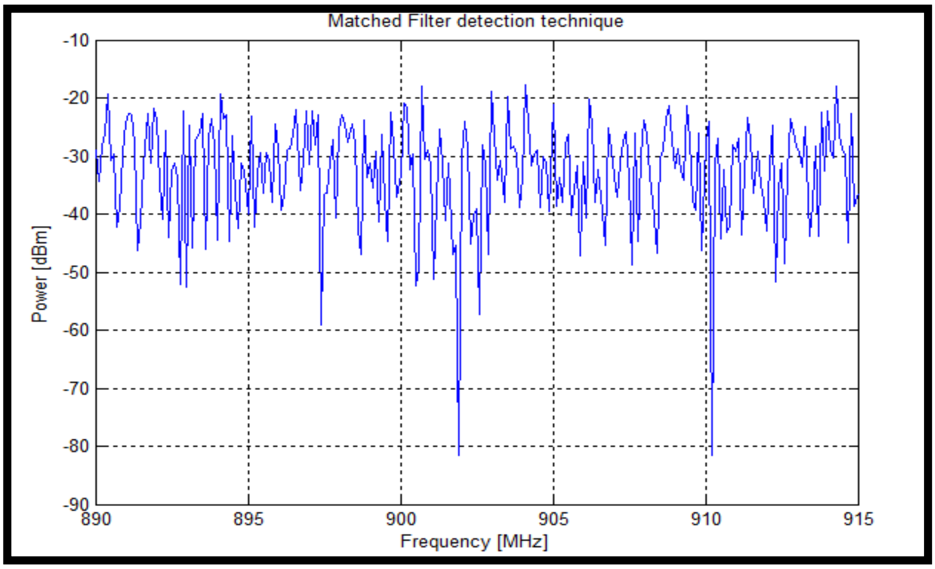


Figure 3-8: Simulation of Matched Filter Detection, Frequency vs. Power in dBm

Frequency [MHz]	Power [dBm]
893	-51
904	-39
908	-81
910	-31

Threshod Value set at -45dBm

Table 3-3: Simulation of Matched Filter Detection, Frequency vs. Power in dBm

In the above figure simulation of Matched filter detector has been done by considering the GSM frequency range. Frequency is varied from 890 MHz to 915MHz and power level varied from -10 dBm to -90 dBm. Here threshold value is fixed at – 45 dBm. Power below -45 dBm indicates the absence of primary user and power above -45 dBm indicates the presence of the primary user.

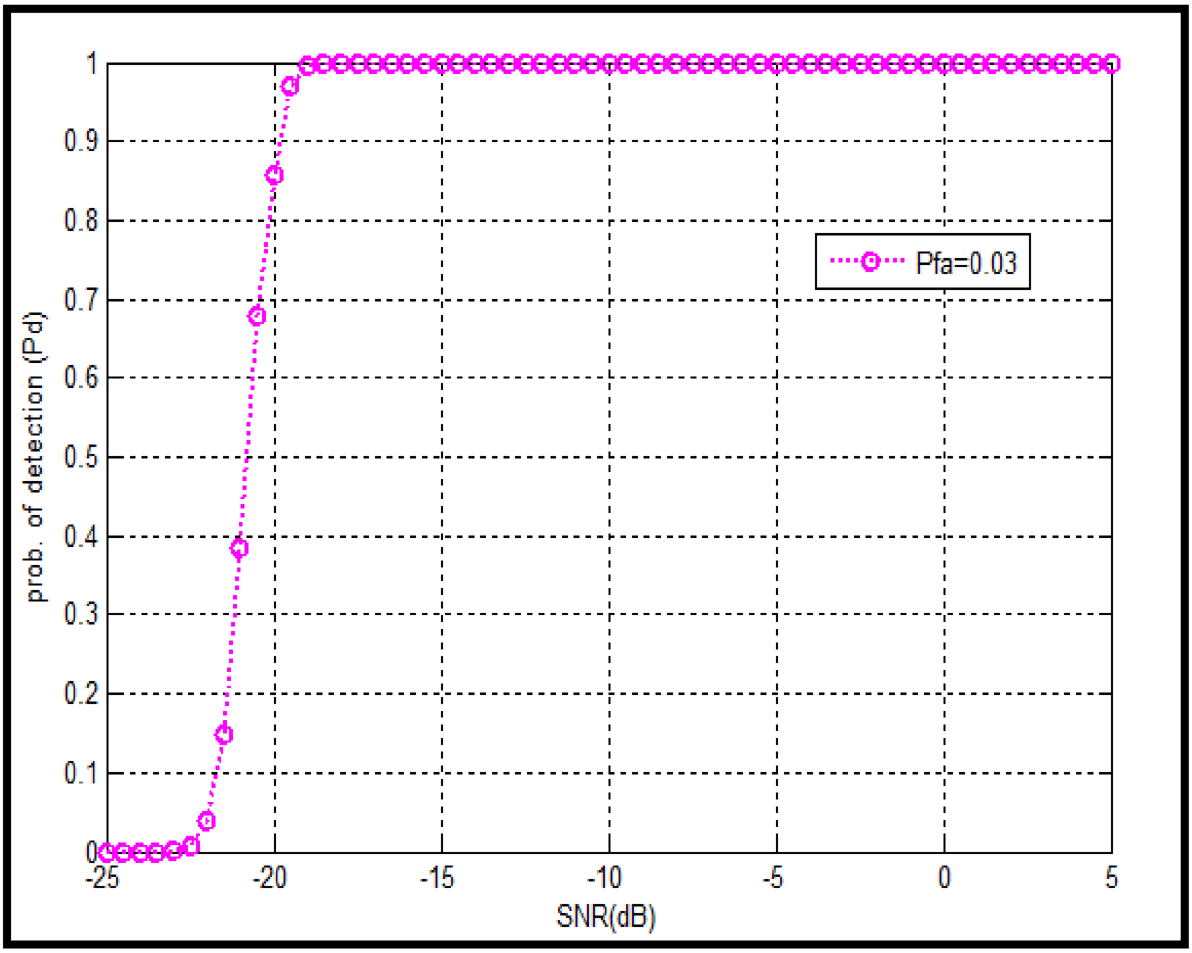


Figure 3-9: Receiver operating characteristics of Cyclostationary detection SNR vs. Pd

SNR [dB]	P_d
-23	0
-22	0.1
-20	0.85
-19	0.9
-18	1

P_f value is

Set at

0.03

Table 3-4: Receiver operating characteristics of Cyclostationary detection SNR vs. Pd

The above figure has been plotted by considering the SNR (dB) and detection probability. The false alarm probability value is taken as 0.03 and SNR is varied from -25dB to 5dB. When the SNR is very small value, then probability of detection is almost zero i.e. less than -22dB. When SNR lies between -22 dB and -20 dB probability of detection of the primary user is linearly increases. Finally, Pd value is reached maximum from -18dB to 5dB. So from the above fig we found that when SNR increases the detection probability is also increases. This method is the best at low SNR values.

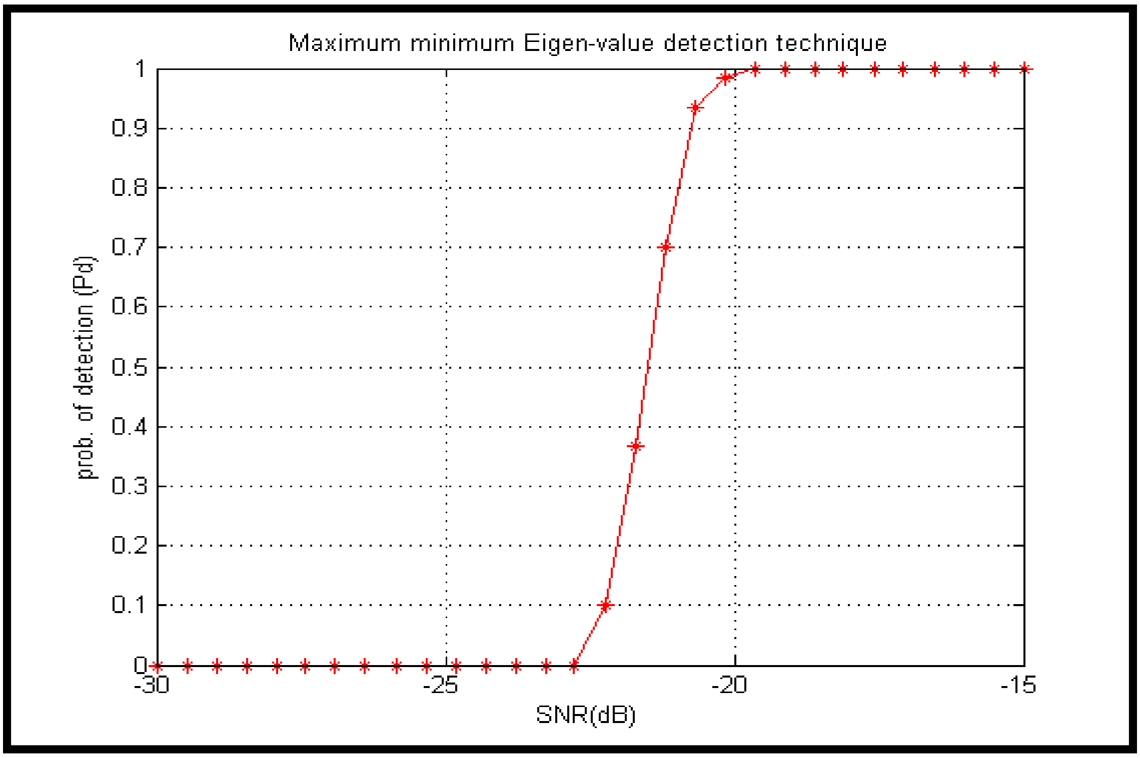


Figure 3-10: Receiver Operating Characteristics for Eigenvalue based Detection Technique SNR vs Pd

SNR [dB]	P_d
-23	0
-22	0.37
-21	0.8
-20	0.98
-19	1

P_f value is

Set at

0.03

Table 3-5: Receiver Operating Characteristics for Eigenvalue based Detection Technique SNR vs Pd

The above figure has been plotted by taking the SNR (dB) and detection probability. The false alarm probability value is taken as 0.03 and SNR is varied from -30dB to -15dB. When the SNR is very small value, then probability of detection is almost zero i.e. less than -22dB. When SNR lies between -22 dB and -20 dB probability of detection of the primary user is linearly increases. Finally Pd value is reached maximum from -20dB to -15dB. So from the above fig we found that when SNR increases the detection probability is also increases.

3.4.2 Performance Comparison of ED, CFD and Eigenvalue Detection

In this section, three spectrum sensing techniques are compared by plotting the graph between SNR in dB and Probability of detection.

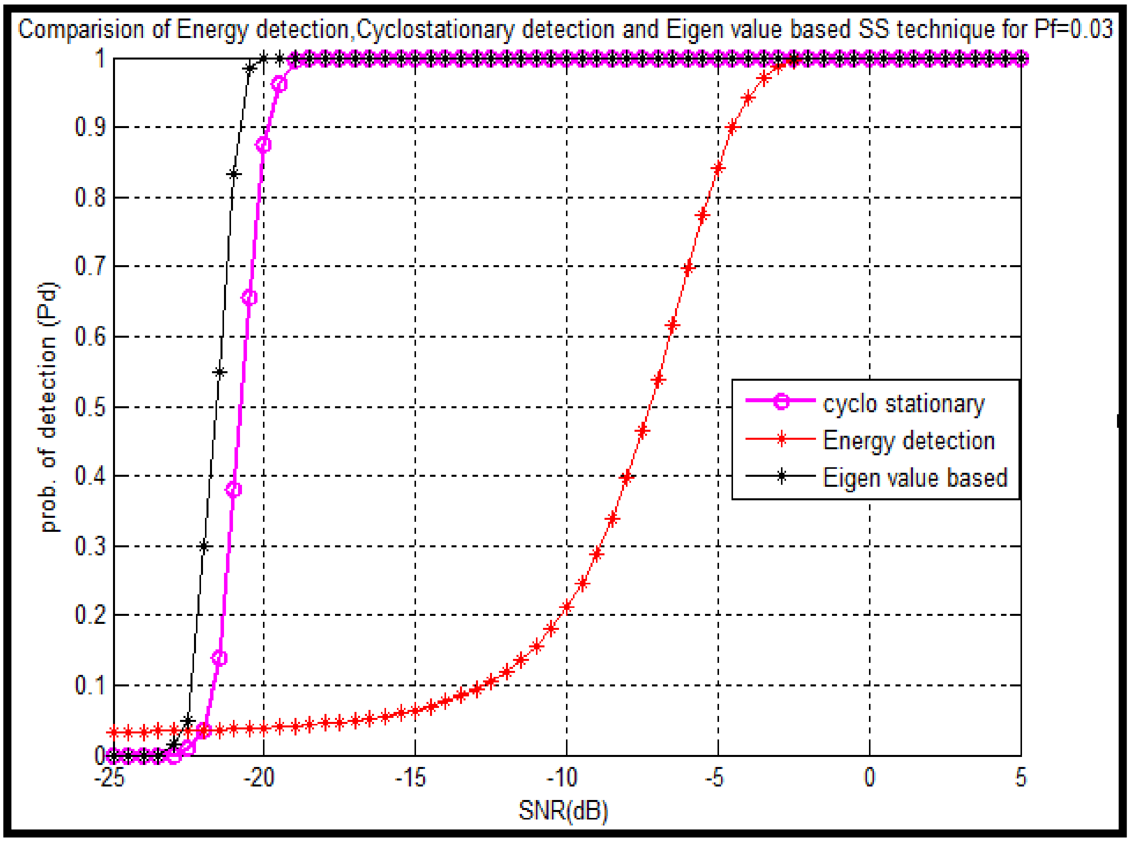


Figure 3-11: Comparison Curves for ED, CFD and Eigenvalue Based Detection

Sensing Method / SNR [dB]	Energy Detection	Cyclosationary	Eigenvalue based
-24	0.05	0	0
-23	0.05	0	0.06
-22	0.05	0.15	0.55
-21	0.05	0.6	0.98
-20	0.05	0.88	1
-19	0.06	0.98	1
5	1	1	1

P_d Values

Table 3-6: Comparison of ED, CFD and Eigenvalue Based Detection

Fig.3-11 explains the comparison of three sensing techniques. The false alarm probability value is taken as 0.03. From the above graph, we found that at low SNR values the best technique is Eigenvalue based detection. So the Energy detection method is not suitable for low SNR values. We can choose Cyclostationary feature detection as the second preference.

4

COOPERATIVE SPECTRUM SENSING TECHNIQUES IN CR NETWORKS

4.1 Introduction

CSS is used to overcome the problems of the hidden primary user problem, fading/shadowing and noise uncertainty. To reduce the overhead on communication, the users share the final single bit decisions regarding H_0 and H_1 rather than the entire decision statistics. The primary objective of cooperative spectrum sensing is to decrease the probability of misdetection, false alarm, sensing time and to increase the detection probability. Cooperative sensing is usually implemented in two stages i.e. detecting and reporting. Cooperative sensing deals with the two channels, one is sensing the channel and another one is reporting channel and uses the control channel to share spectrum sensing result. In the CSS, fusion center plays a significant role. It handles the decisions either 1 or 0. If the primary user is present, then it sends the binary decision 1 or else 0. Based on the decision secondary user occupies the frequency band.

4.1 Centralized Sensing

In centralized sensing, a common receiver plays a significant role. The primary task is to collect the data from secondary users and detects the spectrum availability. The only CRs who's having reliable information can send the own decision to the FC. Based on the FC final decision it broadcasts the information to the other SU's and controls the SU's traffic. FC is known as Access point in Wireless LAN and Base Station in Cellular network. The hard decision rules are combined at a FC to take the final decision. The primary aim is to reduce the fading effects of the wireless channel and improve the performance of detection.

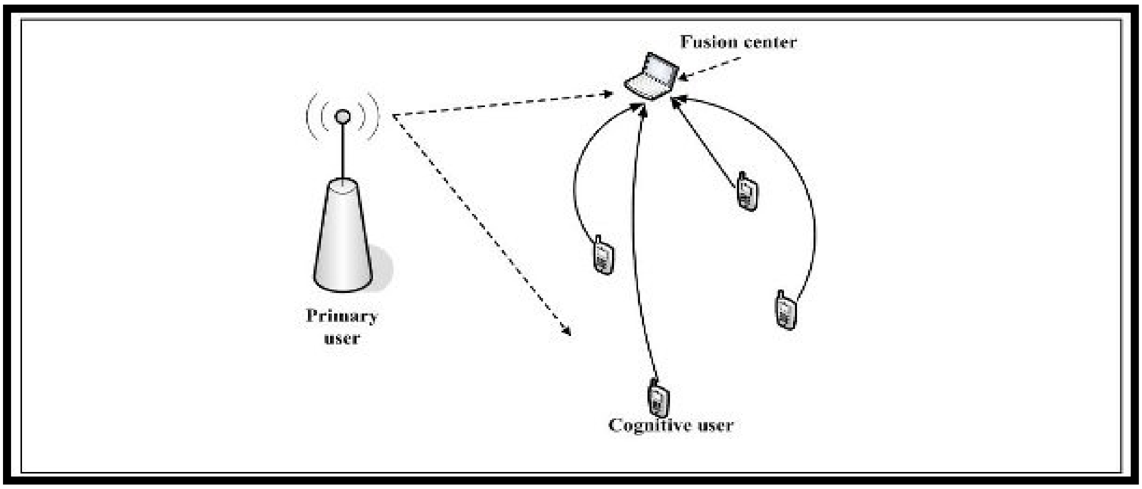


Figure 4-1: Centralized Cooperative Spectrum Sensing

4.2 Decentralized Sensing

The main difference between centralized and decentralized sensing is, the fusion center is not presented in the system model or architecture. In case of decentralized sensing, all the cognitive radios share the data among each other, and the will take their decision as per their used radio spectrum. In decentralized technique, cognitive radios share only final information or final decision to reduce the network overhead due to collaboration.

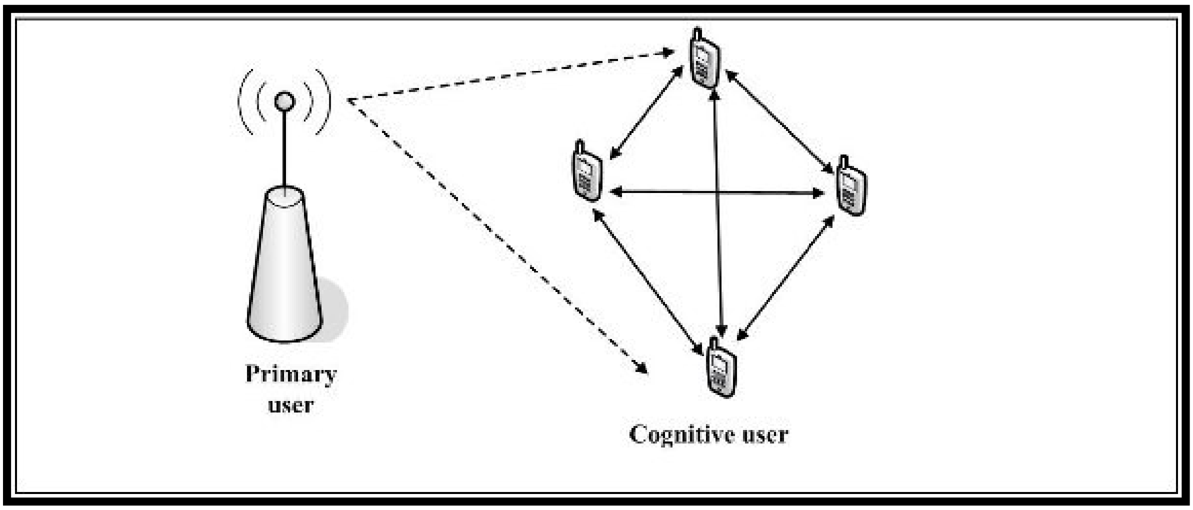


Figure 4-2: Decentralized Cooperative Spectrum Sensing

4.3 External Sensing

Another method for getting the information about spectrum is external detection. In this technique, an external representative does the sensing and send the channel occupancy information to CR's. The primary advantage of external detection is to overcome the problem of hidden PU and also shadowing, fading effects which occur due to noise uncertainty.

4.4 Hard decision rules

CSS deals with the hard decision and soft decision combining techniques. Totally there are six fusion rules are presented in the literature they are soft Optimal Linear mixing, Likelihood Ratio combining, soft Equal Weight combining, and hard decision combined with the AND, OR, and the MAJORITY counting rules. Because of simplicity most famous combining technique is hard decision combining contains OR, AND, and the Majority counting rules. In the implementation of hard decision rules, the fusion centre or central unit produce an n out of M rule that decides on the hypothesis testing at the secondary user. Whenever one secondary user sends output as one i.e., H1, then it comes under OR logic rule similarly if all the secondary users send output as one then it comes under AND logic rule. If majority secondary users send the decision as one then it comes under MAJORITY rule. Assuming uncorrelated decisions, the probability of detection, probability of false alarm and probability of miss detection at the fusion centre are given by [16]:

$$Q_f(K) = \sum_{j=n}^{K} \binom{K}{j} P_f{}^j \, (1 - P_f)^{K-j} \tag{22}$$

$$Q_m(K) = 1 - \sum_{j=n}^{K} \binom{K}{j} P_d{}^j \, (1 - P_d)^{K-j} \tag{23}$$

$$Q_d(K) = 1 - Q_m(K) \tag{24}$$

OR rule:

Performance of detection in CSS using this rule can be calcutaed by putting n=1 in the above equations.

$$Q_d(K) = 1 - \prod_{i=1}^{K}(1 - P_{d,i}) \quad (25)$$

$$Q_f(K) = 1 - \prod_{i=1}^{K}(1 - P_{f,i}) \quad (26)$$

$$Q_m(K) = 1 - Q_d(K) \quad (27)$$

AND rule:

Performance of detection in CSS using this rule will be calculated by putting n=N in the above equations.

$$Q_d(K) = {P_{d,i}}^K \quad (28)$$

$$Q_f(K) = {P_{f,i}}^K \quad (29)$$

$$Q_m(K) = 1 - Q_d(K) \quad (30)$$

MAJORITY rule:

Performance of detection in CSS using this rule can be calculated by putting n= $\left\lfloor \frac{N}{2} \right\rfloor$ in the above equations

$$Q_{d,maj} = \sum_{\left\lfloor \frac{N}{2} \right\rfloor}^{N} \binom{N}{k} \, {P_d}^j \, (1 - P_d)^{K-j} \quad (31)$$

$$Q_{f,maj} = \sum_{\left\lfloor \frac{N}{2} \right\rfloor}^{N} \binom{N}{k} \, {P_f}^j \, (1 - P_f)^{K-j} \quad (32)$$

$$Q_m(K) = 1 - Q_d(K) \quad (33)$$

4.5 System Model of CR Network

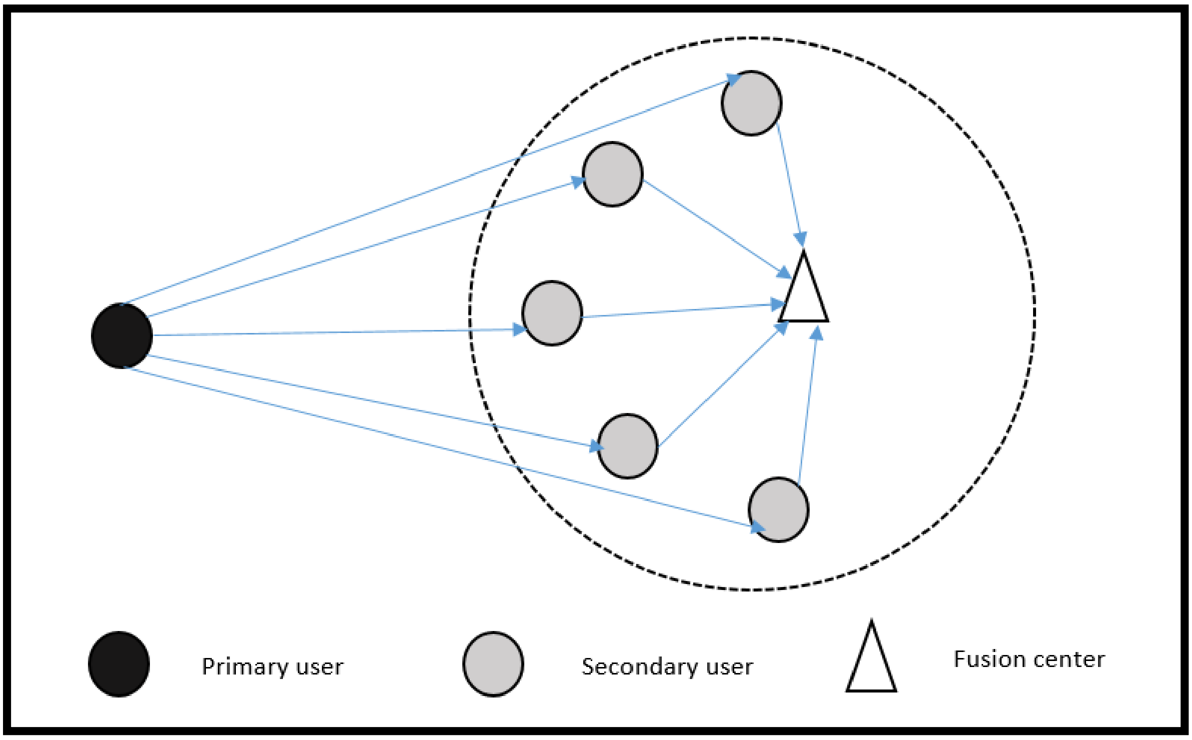


Figure 4-3: System model of CR network

We consider a CR system, which consists of N (network size) number of CR's, K No.of CR's in cooperation and a common receiver (Fusion Center). Fusion Centre functions as a Base Station (BS) in a cellular network and as an Access Point (AP) in WLAN (Wireless Local Area Network). We assume that each CR senses the spectrum independently using the conventional energy detector and sends the local decisions (either binary 1 or 0) to the FC. Fusion Centre performs hard decision fusion then decides the absence or presence of PU.

The local spectrum detection is used to decide between two binary hypothesis testing problems. PU is absent will be considered under hypothesis H0, and PU is present under hypothesis H1.

In the above structure, i number of CRs are present. We consider spectrum sensing at the i^{th} CR only. The signal received by the i^{th} CR is given as [16]:

$$y_i(t) = u_i(t) \qquad \text{H0} \qquad (34)$$

$$y_i(t) = h_i(t)s_i(t) + u_i(t) \qquad \text{H1}$$

Where $u_i(t)$ is the Gaussian noise signal, $h_i(t)$ is the sensing channel gain and $s_i(t)$ is the transmitted signal by the PU.

We presume that the detecting channel gain will not vary with time during the sensing process, so it can be written as $h_i(t)$=h_i. If the sensing channel is error free or non-fading channel, i.e. AWGN then channel gain is equal to unity.

Other assumptions include the following. Prior information of PU is unknown, the channel coherence time is larger than the sensing time. The distance between CR to the PU transmitter is greater when compared to the distance between any two CR's. Hence, each CR faces identical path loss leading to equal signal to noise ratio (SNR) at each CR.

Each CR energy detector output has following distributions

$$Y_i = \begin{cases} \chi^2_{2u} & H0 \\ \chi^2_{2u}(2\gamma_i) & H1 \end{cases} \tag{35}$$

Where Y_i is the energy value of the i^th^ CR is, γ_i is the SNR at the i^th^ CR, χ^2_{2u} indicates a central chi-squared distribution and $\chi^2_{2u}(2\gamma_i)$ a non-central chi-square distribution with 2u degrees of freedom and $u = TW$ is the time bandwidth product .

The average probability of detection, the average probability of false alarm and average probability of dropped detection at i^th^ CR over additive white gaussian noise channel can be represented as [16]:

$$P_{f.i} = Pr\{Y_i > \lambda_i | H0\} = \frac{\Gamma(u, \frac{\lambda_i}{2})}{\Gamma(u)} \tag{36}$$

$$P_{d,i} = Pr\{Y_i > \lambda_i 1\} = Q_u\left(\sqrt{2\gamma_i}, \sqrt{\lambda_i}\right) \tag{37}$$

$$P_{m,i} = 1 - P_{d,i} \tag{38}$$

here, λ_i is the threshold value, Γ (b) is the gamma function, and Γ (b, y) is the incomplete gamma function given as [16]:

$$\Gamma(b, y) = \int_y^\infty t^{b-1}\, e^{-t}\, dt \tag{39}$$

The generalized Marcum Q-function i.e. Q_u (b, y) is given as [12]:

$$Q_u(b, y) = \frac{1}{b^{u-1}} \int_y^\infty t^u\, e^{-\frac{t^2+b^2}{2}}\, I_{u-1}(bt)\, dt \tag{40}$$

Where I_{u-1} (.) is the first kind modified Bessel function with order u-1. Probability of false alarm depends on a threshold value while it does not depend on SNR, so $P_{f,i}$ is same in every fading and non-fading channel.

In the cooperative spectrum sensing at the fusion centre all 1-bit decisions (d_i) also called global decisions are combined together to get the following hard decision logic rules [16].

$$D = \sum_{i=1}^{K} d_i \begin{cases} \geq n, & H1 \\ < n, & H0 \end{cases} \tag{41}$$

Where, n represents the threshold value in "n out of K" rule and it is an integer value. For n equals to 1, it correlates with 'OR rule',for n equals to K, it correlate with 'AND rule' and if $n = {}^{K}\!/_{2}$ it becomes majority rule (half voting rule).

The FC finds the false alarm probability and missed detection probability, by considering the average probability of false alarm and missed detection of each CR. The false alarm probability and miss detection probability are given as [16]:

$$Q_f(K) = \sum_{j=n}^{K} \binom{K}{j} P_f{}^j \, (1 - P_f)^{K-j} = Prob(\tfrac{H1}{H0}) \tag{42}$$

$$Q_m(K) = 1 - \sum_{j=n}^{K} \binom{K}{j} P_d{}^j \, (1 - P_d)^{K-j} = Prob(\tfrac{H0}{H1}) \tag{43}$$

$$Q_d(K) = 1 - Q_m(K) \tag{44}$$

5

PROPOSED TECHNIQUE FOR COOPERATIVE SPECTRUM SENSING OPTIMIZATION

5.1 Introduction

Optimization is required when we need suitable value for any application. In a wireless communication system, different methods are presented for optimization. In cognitive radio technology, we have different parameters and functions for optimization. Some of the relevant parameters to be optimized are sensing time, no of samples, threshold value and number of CR's. In CSS, we have three options for optimization they are the optimum voting rule, optimum threshold, and optimum number of CR's. Some of the functions to be optimized are network throughput, total error probability, and network utility. To obtain required values, we need to maximize the network throughput and utility and minimize the error probability at the fusion centre. In this thesis for optimization of cooperative spectrum sensing, we have used conventional energy detection technique as the sensing method by considering the two functions they are error probability and network utility function. Our aim is to maximize the network utility and minimize the error probability to get optimum voting rule and optimal number of cognitive radios.

5.2 Error Probability

Error Probability is defined at the Fusion Centre in Cooperative Spectrum Sensing. It is defined as the sum of the average probability of false alarm and average probability of miss detection i.e. $Z(K) = Q_f(K) + Q_m(K)$. It should be as minimum as possible. If we consider the prior probability of the presence of primary user and absence of primary user $P(H1)$ and $P(H0)$ respectively then error probability can be defined as [16]:

$$Z(K) = P(H0)Q_f(K) + P(H1)\,Q_m(K) \qquad (45)$$

Where, the probability of fake alarm and the missed detection probability at the fusion center are given by the equations (42) and (43).

5.3 Network Utility Function

Network Utility is a convex function, it shows how efficiently the CR network gets the data about occupancy of spectrum. It should be as maximum as possible. It is given as

$$J(K) = \underbrace{u_1\left(\left(1 - Q_f(K)\right)P(H0) + Q_m(K)P(H1)\right)}_{1} - \underbrace{u_2 Q_m(K)P(H1)}_{2} - \underbrace{u_3 K}_{3} \qquad (46)$$

Where, first part defines the profit of utilizing the spectrum in cognitive radio network, the second part defines the penalty because it uses the busy spectrum and results in harmful interference to the primary user, and third part sets out the cost of the resource of secondary user in cooperation. u_1, u_2 and u_3 are the costs for the three part. The prior probability of the presence of primary user, absence of primary user are $P(H1)$ and $P(H0)$ respectively.

Network Utility function, is defined only with active sensing users as the weighted average of information gain and the resource efficiency (either bandwidth or energy consumption) of the cognitive radio network [17].

In this module, we investigate the optimal voting rule and an optimal number of CR's.

5.4 Optimum Voting rule (Fusion Rule)

Optimal voting rule to maximize the network utility function and minimize the error probability

Optimal voting rule is to find out the optimal value of n denoted as n^* for which we get maximum the network utility function and minimum error probability. Here, we assumed that K is fixed.

The network utility function is given as [17]:

$$J(K) = \underbrace{u_1\left(\left(1 - Q_f(K)\right)P(H0) + Q_m(K)P(H1)\right)}_{1} - \underbrace{u_2 Q_m(K)P(H1)}_{2} - \underbrace{u_3 K}_{3}$$

The error probability is given as [16]:

$$Z(K) = Q_f(K) + Q_m(K) \tag{47}$$

The optimum value of n for cooperative spectrum sensing that minimizes the error probability [12] and maximizes the network utility function is given as:

$$n^* = \min\left(K, \ulcorner \frac{K}{1+\beta} \urcorner\right) \tag{48}$$

Where, $\beta = \frac{\ln(\frac{Pf}{1-Pm})}{\ln(\frac{Pm}{1-Pf})}$

Proof:

Define the function $Z(K)$ obtained by adding $Q_f(K) + Q_m(K)$.

$$Z(K) \cong Q_f(K) + Q_m(K)$$

$$\Delta Z(K) = Z(K+1) - Z(K)$$

Therefore, the difference is given as $Z(K+1) - Z(K)$

$$= \sum_{j=n+1}^{K} \binom{K}{j} [{P_f}^j (1 - P_f)^{K-j} - (1 - P_m)^j P_m^{K-j}] -$$

$$\sum_{j=n}^{K} \binom{K}{j} [{P_f}^j (1 - P_f)^{K-j} - (1 - P_m)^j P_m^{K-j}]$$

$$\Delta Z(K) = 0$$

$$-P_f^{n^*}\left(1 - P_f\right)^{K-n^*} + P_m^{K-n^*}(1 - P_m)^{n^*} = 0$$

On simplifying, we get

$$n^* \approx \left\lceil \frac{K}{1+\beta} \right\rceil$$

Where, $\beta = \frac{\ln(\frac{Pf}{1-Pm})}{\ln(\frac{Pm}{1-Pf})}$

For some values of n we will get the following conclusions:

If P_f and P_m are same, then $\beta \approx 1$. Thus, the optimal n is half of the total number of CR's i.e. $\frac{K}{2}$ (Half voting rule). When $\beta \geq K-1$, that means $P_f \leq P_m^{K-1}$. It shows that $P_f \ll P_m$ for a large value of K and threshold. In this case, 'OR' rule is optimal. If $P_m \ll P_f$ then $\beta \to 0$ and for small values of threshold, AND rule is optimal.

For modeling, discrete signal energy is calculated using the discrete signal received by the secondary user. For AWGN channel, if the received discrete signal is of type

$$y(n) = s(n) + u(n) \qquad H1 \tag{49}$$

Then, the energy of the above signal is:

$$E_1 = \frac{1}{N_0} \sum_n (s(n) + u(n))^2 \tag{50}$$

If the received signal is of type

$$x_2(n) = u(n) \qquad H0 \tag{51}$$

Then, the energy of the above signal is:

$$E_2 = \frac{1}{N_0} \sum_n (u(n))^2 \tag{52}$$

Non-centrality parameter $\lambda_n = \frac{E_S}{N_0}$ = SNR

Where, N_0 is the two sided noise power spectral density, E_S is the received signal energy [27].

$$N_0 = \frac{\sum_n s(n)^2}{2\ SNR} \tag{53}$$

5.5 Optimum number of Cognitive Radios

Optimal number of CR's through maximizing the network utility function and minimizing the error probability

In this case, our problem definition is to get the minimum number of cooperative CR's in CR network to maximize the network utility function and minimize the error probability. Here, we assumed that SNR and threshold are known.

In case of network utility, to find out the optimal number of CR's, we apply 'OR' fusion rule at the FC. Assume that optimal number of CR's is K^* to maximize the network utility function, which is given as [17]:

$$K^* = \arg\max\left(J(K)\right) \tag{54}$$

For 'OR' fusion rule, $Q_d(K)$ and $Q_f(K)$ are given as [17]:

$$Q_d(K) = 1 - \prod_{i=1}^{K}(1 - P_{d,i}) \tag{55}$$

$$Q_f(K) = 1 - \prod_{i=1}^{K}(1 - P_{f,i}) \tag{56}$$

We assumed that SNR and threshold both are same at each CR. Therefore $P_{m,i}$ and $P_{f,i}$ can be represented as P_d and P_f then equation (42), (43) can be written as [17]

$$Q_d(K) = 1 - (1 - P_f)^K \tag{57}$$

$$Q_m(K) = P_m^K \tag{58}$$

Then we have $\frac{\partial J(K)}{\partial K}_{K=K^*} = 0$

$$\frac{\partial J(K)}{\partial K}_{K=K^*} = J(K+1) - J(K)$$

$$= -u_1\, P(H0)P_f\left(1 - P_f\right)^K + (u_1 - u_2)P(H1)(P_m - 1)P_m^K + u_3 = 0$$

The above equation is very difficult to solve, also called 'transcendental equation.' .To make it accurate u_3 is ignored. Hence:

$$-u_1 P(H0)P_f\left(1 - P_f\right)^{K^*} + (u_1 - u_2)P(H1)(P_m - 1)P_m^{K^*} = 0$$

We obtained the result as [13]:

$$K^* = \min(N, \max\left(\left\lceil \frac{\ln \frac{(u_1-u_2)P(H1)(1-P_m)}{u_1 P(H0) P_f}}{ln \frac{(1-P_f)}{P_m}} \right\rceil\right)) \tag{59}$$

In case of error probability, to find out the optimal number of CR's, we apply 'majority rule' at the FC. From the equations (39), (40) and (41) to get the optimal number of CR's we need to differentiate (45) with respect to K by considering the prior probabilities (i.e. $Z(K) = P(H0)Q_f(K) + P(H1)Q_m(K)$) and equate the result to zero.

Then Optimal K is given as [16]:

$$K^* = \min\left(N, \left\lceil \frac{N \ln\left(\frac{Pm}{1-Pf}\right) + \ln\left(\frac{P(H1)}{P(H0)}\right)}{\ln\left(\frac{Pf}{1-Pm}\right) + \ln\left(\frac{Pm}{1-Pf}\right)} \right\rceil\right) \tag{60}$$

5.6 Optimum Energy Threshold Value

For the calculation of optimal value of threshold λ* , we consider that number of cognitive radios, optimal n and signal to noise ratio are known such that error probability is minimum. Here, we have plotted in fig 5-2 error probability with different threshold values. Each optimal n should have one optimal threshold value at which error probability is minimum i.e. $(Q_{f+}Q_m)$ is minimum at optimal threshold value.

$$\lambda^* = arg\{\min(Q_f + Q_m)\} \tag{61}$$

For optimal energy detection threshold value

$$\frac{\partial Q_f}{\partial \lambda} + \frac{\partial Q_m}{\partial \lambda} = 0 \tag{62}$$

Using the equations (42) and (43), the solution to equation (62) can be achieved numerically. The solution is the optimal detection threshold value.

In case of network utility,

$$\lambda^* = arg\{\max(J(K))\} \tag{63}$$

For optimal energy detection threshold value

$$\frac{\partial J(K)}{\partial \lambda} = 0 \tag{64}$$

The solution to equation (64) will be achieved numerically. Optimal detection threshold is the main solution.

5.7 Simulation Study and Analysis

This thesis optimizes the voting rule and the No.of Cognitive radios in CSS through maximizing the network utility and minimizing the error probability. A simulation study is carried out in MATLAB. We set cost values at u_1=0.2, u_2=0.8, u_3=0.005 and prior probabilities at $P(H0)$=0.6, $P(H1)$=0.4. We have considered SNR=10dB and K=6.

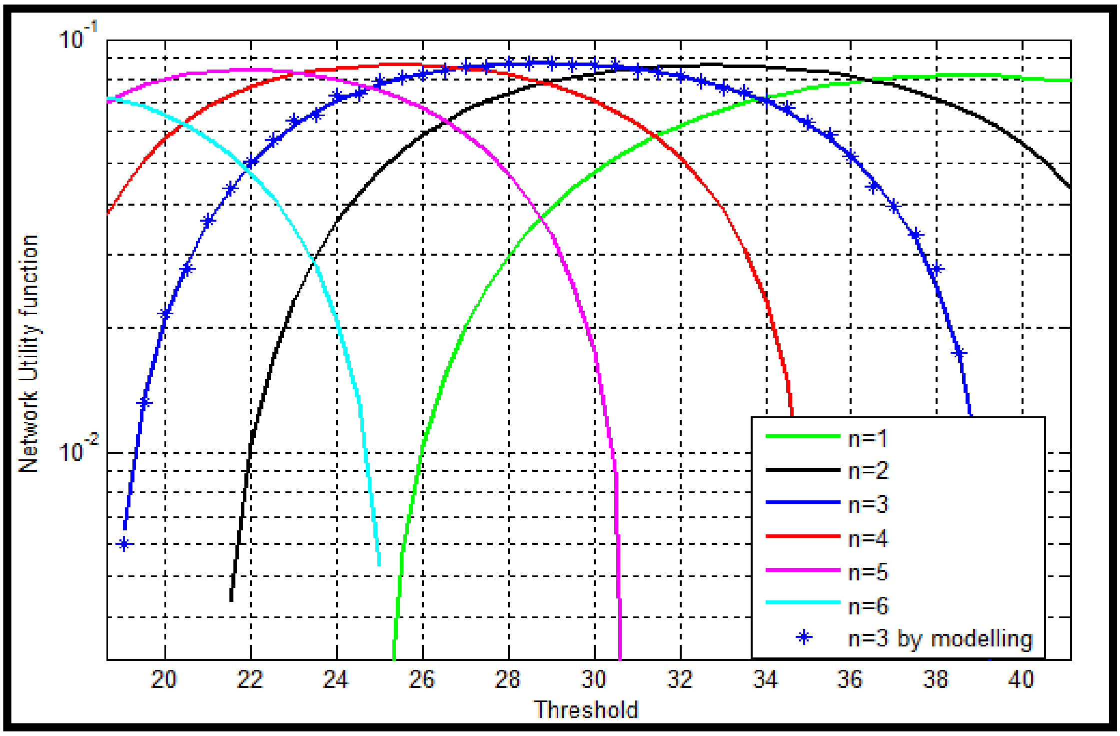


Figure 5-1: Network utility function versus energy threshold over AWGN channel. Voting rules are n=1, 2, 3….6.

Optimal n	Network Utility	Threshold value
1	~0.080	40
2	~0.085	33
3	~0.090	29
4	~0.086	26
5	~0.082	22.5
6	~0.070	18

Table 5-1: Network utility function versus energy threshold over AWGN channel. Voting rules are n=1, 2, 3….6.

Fig.5-1 shows the variation of network utility function for various values of energy threshold and number of CR's. Here the network utility is maximum for n=3 and minimum for n=6 and n=1. So, we can achieve maximum network utility by considering the half number of CR's, hence half voting rule is optimal. For theoretical verification of half voting rule for n=3 to get maximum utility we have used the equations from (49) to (53). Optimal energy detection threshold value for each and every value of n is obtained. For optimal voting rule i.e. at n=3 optimal threshold value is 29 and it varied for different values of n.

.

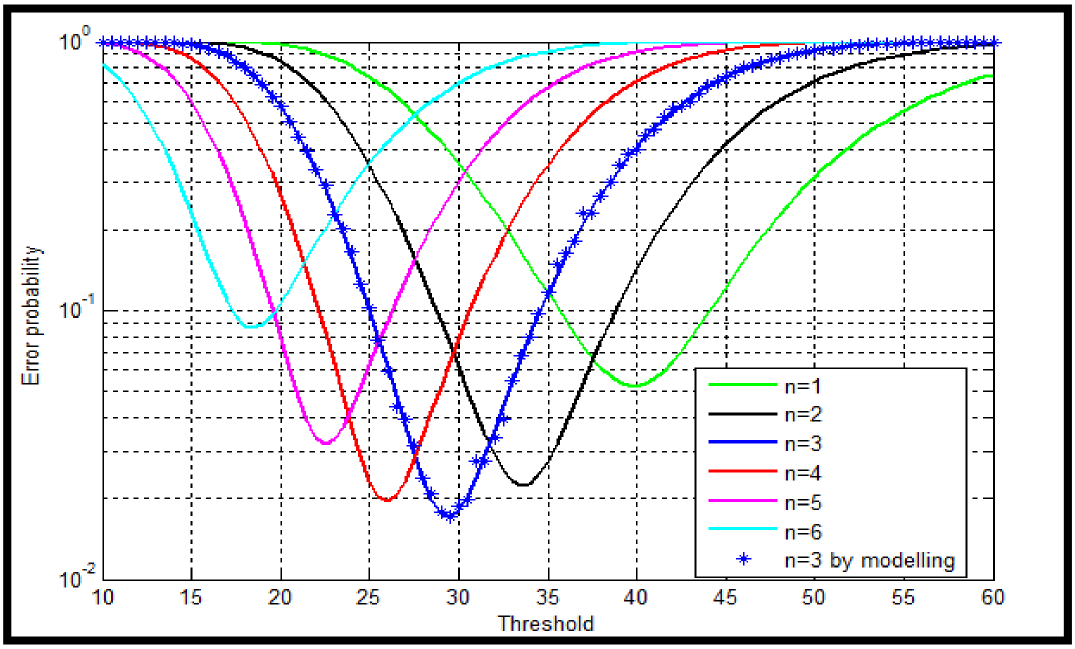


Figure 5-2: Error probability versus energy threshold over AWGN channel. Voting rules are n=1, 2, 3…6.

Optimal n	Error Probability	Threshold value
1	~0.052	40
2	~0.023	33
3	~0.018	29
4	~0.020	26
5	~0.033	22.5
6	~0.090	18

Table 5-2: Error probability versus energy threshold over AWGN channel. Voting rules are n=1, 2, 3…6.

Fig.5-2 depicts the variation of error probability for various values of energy threshold and number of CR's. Here we have observed that the error probability is minimum for n=3 and maximum for n=6 and n=1. So, out of the total number of user's half users performs better than the other user's, hence half voting rule is optimal. For theoretical verification of half voting rule for n=3 to get minimum error probability we have used the equations from (49) to (53). Optimal energy detection threshold value for each and every value of n is obtained. For optimal voting rule i.e. at n=3 optimal threshold value is 29 and it varied for different values of n.

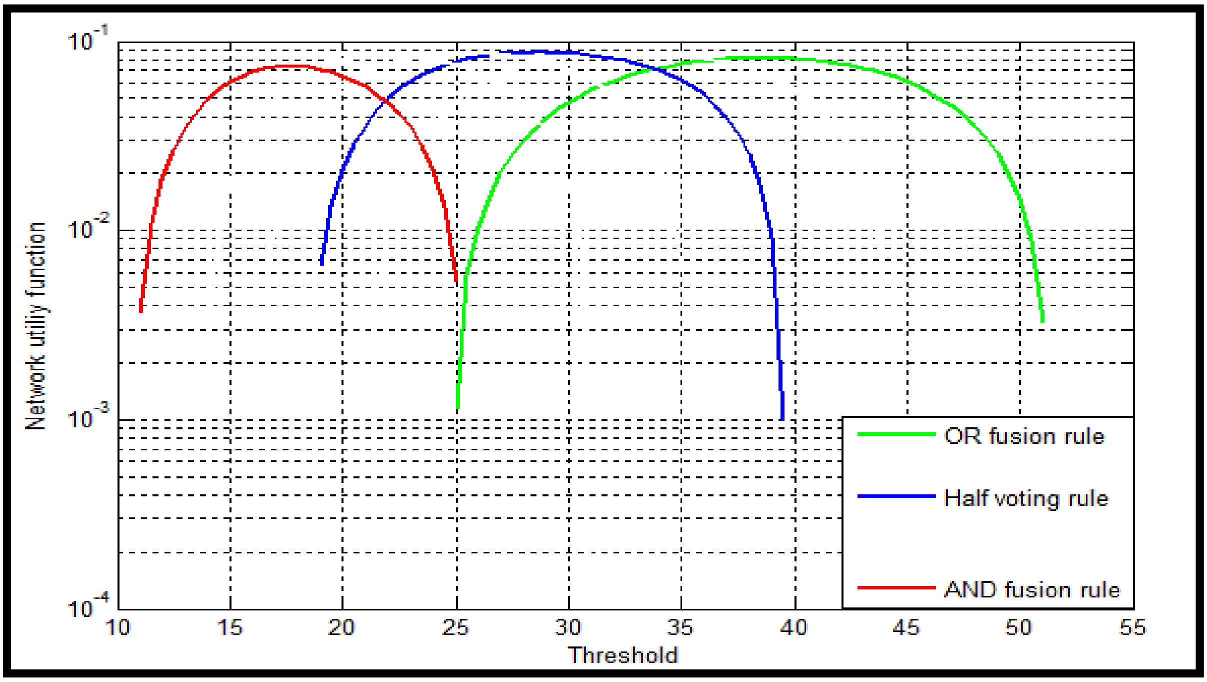


Figure 5-3: Comparison of fusion rules for different thresholds. Voting rules are n=1 i.e. OR rule, n=3 i.e. half voting rule, n=6 i.e. AND rule, considering network utility function.

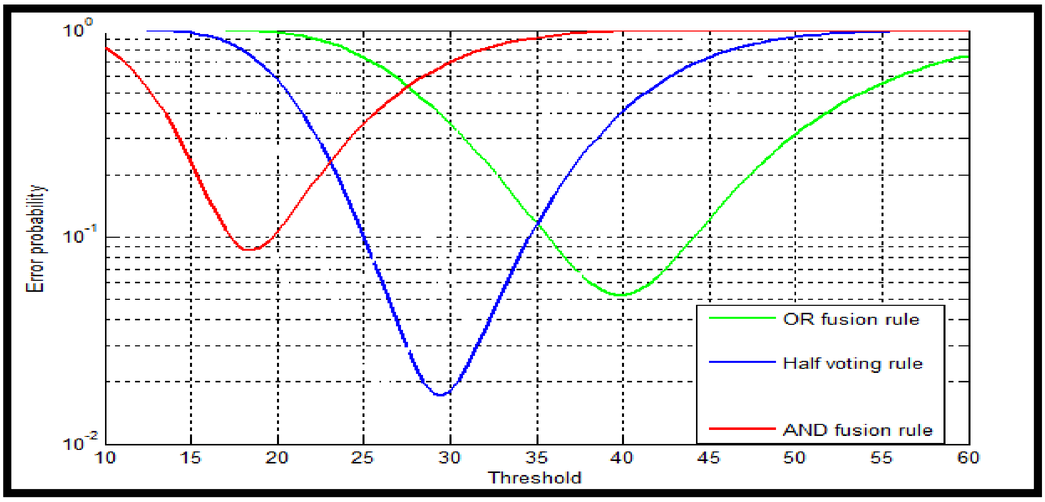


Figure 5-4: Comparison of fusion rules for different thresholds. Voting rules are n=1 i.e. OR rule, n=3 i.e. half voting rule, n=6 i.e. AND rule, considering error probability.

Fig.5-3 and Fig.5-4 show the comparison of different hard decision rules at the fusion center for showing the network utility versus energy threshold and error probability versus energy threshold respectively. From these two figures, we have concluded that half voting rule must be implemented for achieving better network utility with minimum error probability.

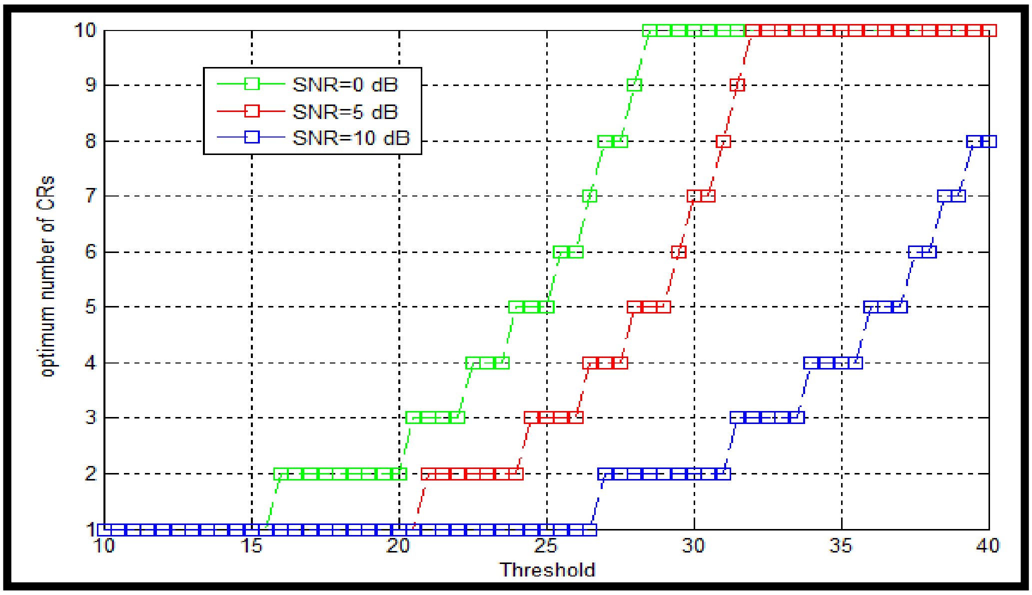


Figure 5-5: Optimal number of CR's versus detection threshold with SNR=0, 5,10dB and K =10 (considering network utility function).

Threshold Value \ SNR [dB]	0 dB	5 dB	10 dB
18	2	1	1
23	4	2	1
30	10	7	2
40	10	10	8

Optimal No.of CR's

Table 5-3: Optimal number of CR's versus detection threshold with SNR=0, 5,10dB and K =10 (considering network utility function).

Fig.5-5 shows the optimal number of CR's for different values of energy threshold varies from 10 to 40 by considering the three different SNR values 0, 5, 10dB. From the graph, we concluded a less number of CR's are required for lower values of SNR and threshold, and more number of CR's are needed for the higher value of SNR and threshold.

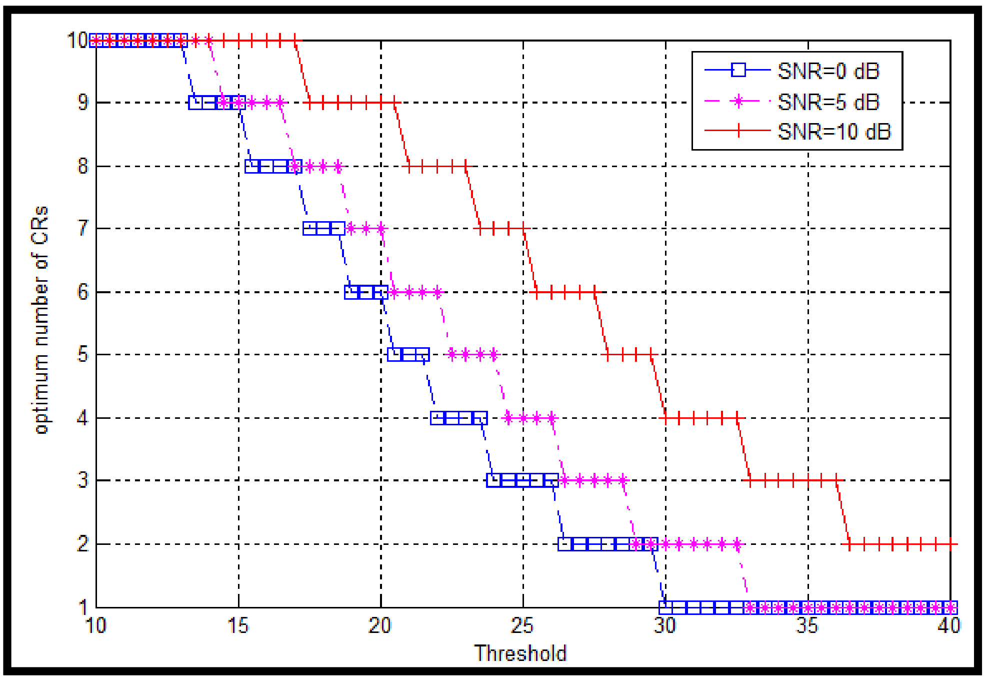


Figure 5-6. Optimal number of CR's versus detection threshold with SNR=0, 5,10dB, K =10 (considering error probability).

Threshold Value \ SNR [dB]	0 dB	5 dB	10 dB
10	10	10	10
20	6	7	9
30	1	2	4
40	1	1	2

Optimal No.of CR's

Table 5-4: Optimal number of CR's versus detection threshold with SNR=0, 5,10dB, K =10 (considering error probability).

Fig.5-6 shows the optimal number of CR's for different values of energy threshold varies from 10 to 40 by considering the three different SNR values 0, 5, 10dB. From the graph, we concluded more number of CR's are required for lower values of SNR and threshold, and less number of CR's are needed for the higher value of SNR and threshold.

6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

In wireless communication systems, electromagnetic spectrum is a most valuable resource. It has been a main research topic from last several decades. The famous technology which enables the white spaces or spectrum holes is cognitive radio. The most important element of CR is to detect the spectrum repeatedly and adapts the parameters in any wireless environment. CR is an attempt to use the uncommitted spectrum more effectively. Efficient use of free frequency band and limited interference with the licensed users can be depends on the use of the spectrum sensing method. Most of the challenges raised by the cognitive radios can be earased by using the suitable spectrum sensing techniques.

Cognitive Radio network development must be needed in the interaction and involvement of numerous advanced methods, it contains de-centralized spectrum sensing, management of interference, and collaborative communications. In wireless communication, to realize the cognitive radio network for systematic use of the electromagnetic spectrum, the technique used in detecting the interference and/or sensing the spectrum must be more reliable. Hence, primary user will not face any problem from cognitive radio system to use their allocated spectrum.In this thesis, we have explained and compared the different spectrum sensing methods. By considering the speed of estimation, accuracies and computational complexities of each method we have used conventional energy detection technique in CSS. CSS is used to overcome the hidden PU problem, fading/shadowing effects. Optimization of CSS is a crucial task to get required/suitable values in any application. The primary objective of this thesis was to find out the optimal voting rule, optimal number of cognitive radios in CSS and optimal energy detection threshold value. It has been noticed that half voting rule satisfies the optimality condition for a maximum network utility function and minimum error probability. By employing different hard decision fusion rules in cooperative spectrum sensing, we found an optimal number of CR’s through maximizing the network utility and minimizing the error probability for different values of SNR over AWGN channel. A method has been obtained to solve the optimal detection threshold, numerically. It has been found that the suitable selection of CR can achieve better utility function with minimum error probability for any wireless environment.

6.2 Future Scope of Research

Further, the performance of CSS and optimization of CSS can be improved by considering the clusters. In cluster based CSS cluster head plays a major role. Cluster head will be selected by considering the reporting channel gain into account. A secondary user who is having the maximum gain for reporting the channel in a cluster will lead the group. The primary task of the leader is to gather the detected signals from each and every secondary user in the same cluster and this collected result will be transferred to the common receiver i.e. fusion centre. Later on common receiver send back the global decision after deciding the occupation of the spectrum to the respective cluster heads. Hence, the accuracy of the correct decision will be improved, and primary user emulation effects (PUE’s) will get reduced.

BIBLIOGRAPHY

[1] Federal Communications Commission, "Notice of proposed rulemaking and order: Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies," ET Docket No. 03-108, Feb. 2005.

[2] Paul Kolodzy, and Interference Avoidance, "Spectrum policy task force," Federal Communication Commission, Washington, DC, Rep. ET Docket 02-135, 2002.

[3] H. Ronald Coase, "The federal communications commission," Journal of law and economics vol. 2, pp.1-40, 1959.

[4] Joseph Mitola, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," 2000.

[5] Simon Haykin, "Cognitive radio: brain-empowered wireless communications," IEEE Journal on selected Areas in Communications, vol. 23-2, pp. 201-220, 2005.

[6] Clancy III, Charles Thomas, "Dynamic spectrum access in cognitive radio networks," PhD diss., University of Maryland, 2006.

[7] I. F. Akyildiz, W. Y. Lee, M.C. Vuran and S. Mohanty, "NeXt Generation / Dynamic Spectrum Access / Cognitive Radio Wireless Networks: A Survey," Computer Networks Journal (Elsevier), vol. 50, pp. 2127-2159, 2006.

[8] Ali Gorcin and Bhaskar Thiagarajan, "A Signal Identification Application for Cognitive radio," SDR Forum Technical Conference, 2007.

[9] Parikshit Karnik and Sagar Dumbre, "Transmitter Detection Techniques for Spectrum Sensing in CR Networks," Department of Electrical and Computer Engineering, Georgia Institute of Technology, 2004.

[10] Marko Höyhtyä, Atso Hekkala, Marcos D. Katz, and Aarne Mämmelä, "Spectrum awareness: techniques and challenges for active spectrum sensing," In Cognitive Wireless Networks, pp. 353-372, Springer Netherlands, 2007.

[11] Harry Urkowitz, "Energy detection of unknown deterministic signals," Proceedings of the IEEE, vol. 55- 4, pp.523-531, 1967.

[12] Ashish Bagwari, and Brahmjit Singh, "Comparative performance evaluation of spectrum sensing techniques for cognitive radio networks," In Computational

Intelligence and Communication Networks, Fourth International Conference on, pp. 98-105, IEEE, 2012.

[13] Tevfik Yucek and Huseyin Arslan, “A survey of spectrum sensing algorithms for cognitive radio applications” In IEEE communication surveys and tutorials vol. 11. No.1, first quarter 2009.

[14] G. Ganesan and Y. G. Li, “Cooperative spectrum sensing in cognitive radio networks," in Proc. IEEE Symp. New Frontiers Dynamic Spectrum Access Networks (DySPAN’05), Baltimore, USA, pp. 137-143, Nov. 2005.

[15] A. Ghasemi and E. S. Sousa, “Collaborative spectrum sensing for opportunistic access in fading environments," in Proc. IEEE Symp. New Frontiers in Dynamic Spectrum Access Networks (DySPAN’05), Baltimore, USA, pp. 131-136, Nov. 2005.

[16] Wei Zhang, Ranjan K. Mallik and Khaled Ben Letaief, “Optimization of Cooperative Spectrum Sensing with Energy Detection in Cognitive Radio Networks”, IEEE transactions on wireless communications, vol. 8, no. 12, Dec 2009.

[17] Suwen Wu, Ming Zhao and Jinkang Zhu, “Optimal Number of Secondary Users through Maximizing Utility in Cooperative spectrum sensing” IEEE Vehicular Technology Conference Fall, 5 pages, doi:10.11109/VETECF.2009.5379043, Sept 2009.

[18] Vidyadhar Reddy G, N.S. Murthy, “Optimization of cooperative spectrum sensing under AWGN and Rayleigh channel in cognitive radio network”, IEEE ICACC, Pages 126-129, 2013.

[19] James O’Daniell Neel, “Analysis and design of cognitive radio networks and distributed radio resource management algorithms,” PhD diss., Virginia Polytechnic Institute and State University, 2006.

[20] Joseph Mitola, and Gerald Q. Maguire Jr., “Cognitive radio: making software radios more personal,” IEEE Personal Communications, vol. 6-4, pp. 13-18, 1999.

[21] D. B Rawat, G. Yan, and C. Bajracharya, “Signal processing techniques for spectrum sensing in cognitive radio networks,” International Journal of Ultra Wideband Communications and Systems, vol. 10, pp. 1-10, 2010.

[22] Cheng-Xiang Wang, Hsiao-Hwa Chen, Xuemin Hong, and Mohsen Guizani, "Cognitive radio network management," Vehicular Technology Magazine, IEEE, vol. 3-1, pp. 28-35, 2008.

[23] Ying-chang Liang, Yong Hong Zeng, Edward C.Y.Peh and Anh Tuan Hoang, "Sensing Throughtput Tradeoff for Cognitive Radio Networks," IEEE transactions on wireless communication.Vol 7, No 4. April 2008.

[24] M.H Mohamad, Haw cuiwen and M. Ismail "Matched Filter Detetion for GSM band," 1st IEEE International Symposium on Telecommunication Technologies.

[25] Gardner, A. William "Exploitation of spectral redundancy in cyclostationary signals," Signal Processing Magazine, IEEE, vol.8-2, pp.14-36, 1991.

[26] Miao Yang, Jiaping an, Xiangyuan Bu, Leisun, "An improved Eigen-value based algorithm for cooperative spectrum sensing," 2010.

[27] Harry Hrkowitz, "Energy Detection of Unknown Deterministic Signals" Proceeding of the IEEE, Vol. 55, Issue no.4, and pg. no. 523 –531, 1967.

Online Resources:

1. www.wikipedia.org

2. www.google.com – Search Engine for data and images

DISSEMINATION

Bommena Pruthviraj Kumar, Deepa Das and Susmita Das, **"Cooperative Spectrum Sensing Optimization through Maximizing the Network Utility and Minimizing the Error Probability"** *IEEE Global Conference on Communication Technologies (GCCT'15),* Nagar Coil, Kanyakumari, Tamilnadu, 23rd - 24th April 2015.